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[Continued on page (III) of Cover.

ELECTRICALLY MANUFACTURED STEELS

By H. A. SIEVEKING, M.Sc., Associate Member.*

(Paper first received 28th February, and in revised form 20th July, 1939: read before the NORTH MIDLAND CENTRE 18th November, 1939, also before the NORTH-EASTERN CENTRE 8th January, before the WESTERN CENTRE 15th January, before the SHEFFIELD SUB-CENTRE 17th January, before the TEES-SIDE SUB-CENTRE 3rd April, and before the WEST WALES SUB-CENTRE 4th April, 1940. The paper would also have been read and discussed before THE INSTITUTION on the 9th November, 1939, but the meeting was cancelled owing to the war.)

SUMMARY

Following a brief description of the two principal types of electric furnaces used, the main products are discussed from a metallurgical standpoint and the advantages and disadvantages of the two types of furnaces for meeting specific requirements are reviewed.

Electricity consumptions are next dealt with and operating results for 20 arc and 25 induction furnaces are given. The approximate allocation of the electricity consumed is stated. The effect of the form of tariff and methods of operation in the factory on the cost of electric steel is also discussed, and some indication is given of the means whereby the costs may be kept in check.

The effect of both types of furnace load on a supply authority's system is next dealt with and, by means of formulae developed in Appendix 1, the characteristics of the arc furnace are shown and an estimate of the short-circuit conditions is given. Typical load curves for both types of furnace are introduced.

To determine the present position of electric steels, the relative outputs of all classes of steel and electric steel are investigated for the eleven major steel-producing countries of the world. A detailed analysis covering a period of 21 years is made for the three countries having the largest outputs of steel, namely the U.S.A., Germany, and Great Britain, and the influence of national and international economic conditions is pointed out.

Finally, it is emphasized that the present production of electric steels forms a small proportion of the total output in Great Britain, and a suggestion is made as to the direction in which developments may be expected.

(1) DESCRIPTION OF THE FURNACES USED

For the manufacture of steel by the electric process two types of furnace have been developed—the arc and the high-frequency (h.f.) induction types. The low-frequency induction type is also occasionally used, but so rarely that its consideration in this paper cannot be justified.

Arc furnaces are used for melting or for keeping molten metal hot, and are usually of the vertical 3-phase 3-electrode type. Such a furnace is shown in cross-section in Fig. 1, while Fig. 2 shows a typical installation.

Essentially the furnace comprises a refractory hearth, which may be of "basic" (e.g. magnesite, MgO) or "acid" (e.g. silica, SiO_2) material as required, and in which the charge is placed; the necessary heat is obtained by electric arcs formed between the charge and the electrodes, which project through the roof in triangular formation. In general, an acid lining is cheaper but this type of lining is "dead," i.e. does not allow of impurities being removed from the bath; whereas the more expensive basic lining is suitable for refining.

Power input is maintained at the desired value by

movement of the electrodes towards or away from the bath, i.e. by decreasing or increasing the arc length. Further control is obtained by providing various voltage tapings on the transformer supplying the furnace.

The electrodes are made of suitable diameter, dependent on the capacity, and may be of graphite or of amorphous carbon. The latter are poorer electrical conductors (Table 1) and therefore require to be of greater diameter than graphite electrodes; further, they are more brittle, and consequently involve greater risk of carbon falling into the charge. Nevertheless, such electrodes

Table 1

CHARACTERISTICS OF AMORPHOUS CARBON AND GRAPHITE ELECTRODES

Item	Amorphous carbon	Graphite
Specific gravity	1.80	2.10
Specific resistance, ohms per sq. in. per foot run	0.018	0.00385
Maximum current loading, amp. per sq. in.	50	125
Oxidation temperature, ° C. ..	435	660
Approximate mean consumption, lb. per 1 000 units (kWh) carried ..	44	17.5
Approximate relative price per lb. . .	1	3
Thermal conductivity, watts per in. cube	1.38	3.10

are cheap to use and can be employed with advantage in certain cases.

The position of the electrodes is adjusted either by hand or automatically. Hand adjustment is simple but gives rise to violent fluctuations of power, and some form of automatic control, consisting of an electric motor or a hydraulic servo motor on each electrode, is to be preferred. The control impulse is electrical in both cases, and may be made proportional to the current flowing or to the arc voltage and current flow combined. A combined impulse gives the closest regulation, but it appears immaterial whether the electrode is moved by an electric or a hydraulic motor. Though some authorities claim smoother operation with hydraulic control, in the author's opinion there is no appreciable difference—given a good modern design in either case.

The roof of the furnace, irrespective of the body, is lined with "acid" or silica bricks for the sake of economy. Alternatively, Sillimanite or high-alumina firebricks are becoming popular where the operation is intermittent.

* Central Electricity Board.

The electrode bosses are water-cooled to prevent overheating and electrode damage.

A special transformer is required for use with such a furnace, for two reasons:—

(a) The reactance must be high, in order to limit the current when the arc is struck or in the event of a short-circuit occurring in service. In fact, separate reactances are frequently installed which may be short-circuited at a certain stage.

the United States, and the abolition of the transformer cubicle may be looked forward to as a possible improvement in the near future.

Arc furnaces may be charged either by hand from the side, or by machine from the side, or from the top by removing the roof. With a compact charge, mechanical feeding is to be preferred because of its rapidity, but where the charge is bulky in proportion to its weight hand feeding will often be as satisfactory and economical

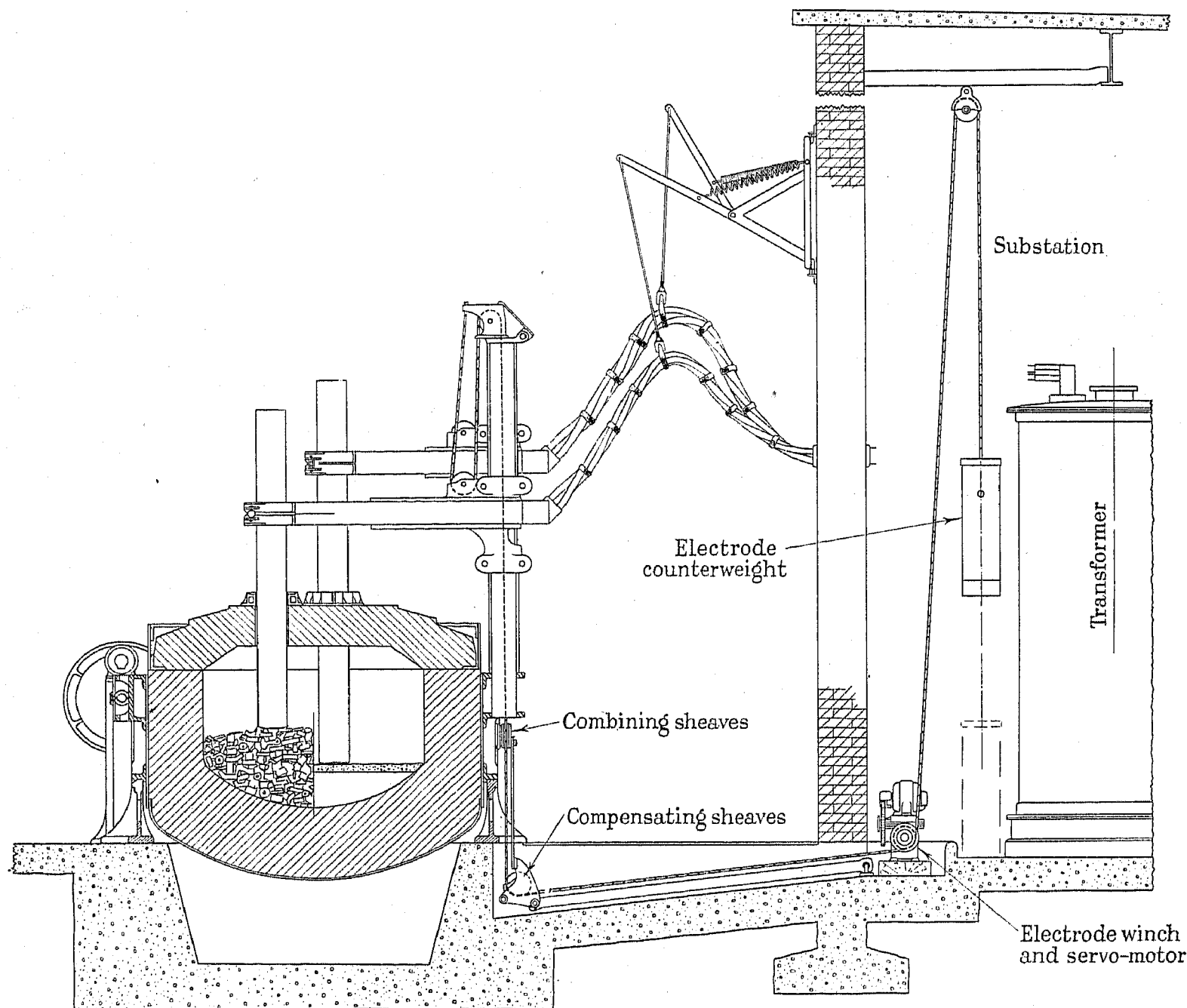


Fig. 1

(b) The primary has several tapplings in order to allow of voltage variation during service. The number of tapplings is commonly 5, but may be 8 or more. The tapplings are usually arranged in two groups, corresponding to star and delta connection of the transformer; the range met with to-day is from a maximum of 250 down to a minimum of 60 volts.

Since heavy currents are taken, the transformer is placed as close to the furnace as possible, but to minimize the fire risk it is located in a separate chamber in which can also be placed the electrode control gear and meter panels. The development of fireproof insulating material to replace oil in the transformer has been advanced in

as a mechanical method. Roof charging has the particular advantage that the depth of cold charge possible is greater than with side feeding.

Pouring is effected by tilting the furnace, either with the help of an electric motor or a hydraulic ram or, occasionally, by hand. The material escapes through a suitably placed spout.

The transformer capacity varies with the duty and size of the furnace. In Table 2 are shown some common sizes of furnace with appropriate (modern) transformer capacities for melting a solid charge or "holding" or refining a molten charge; but these values are by no means rigidly adhered to.

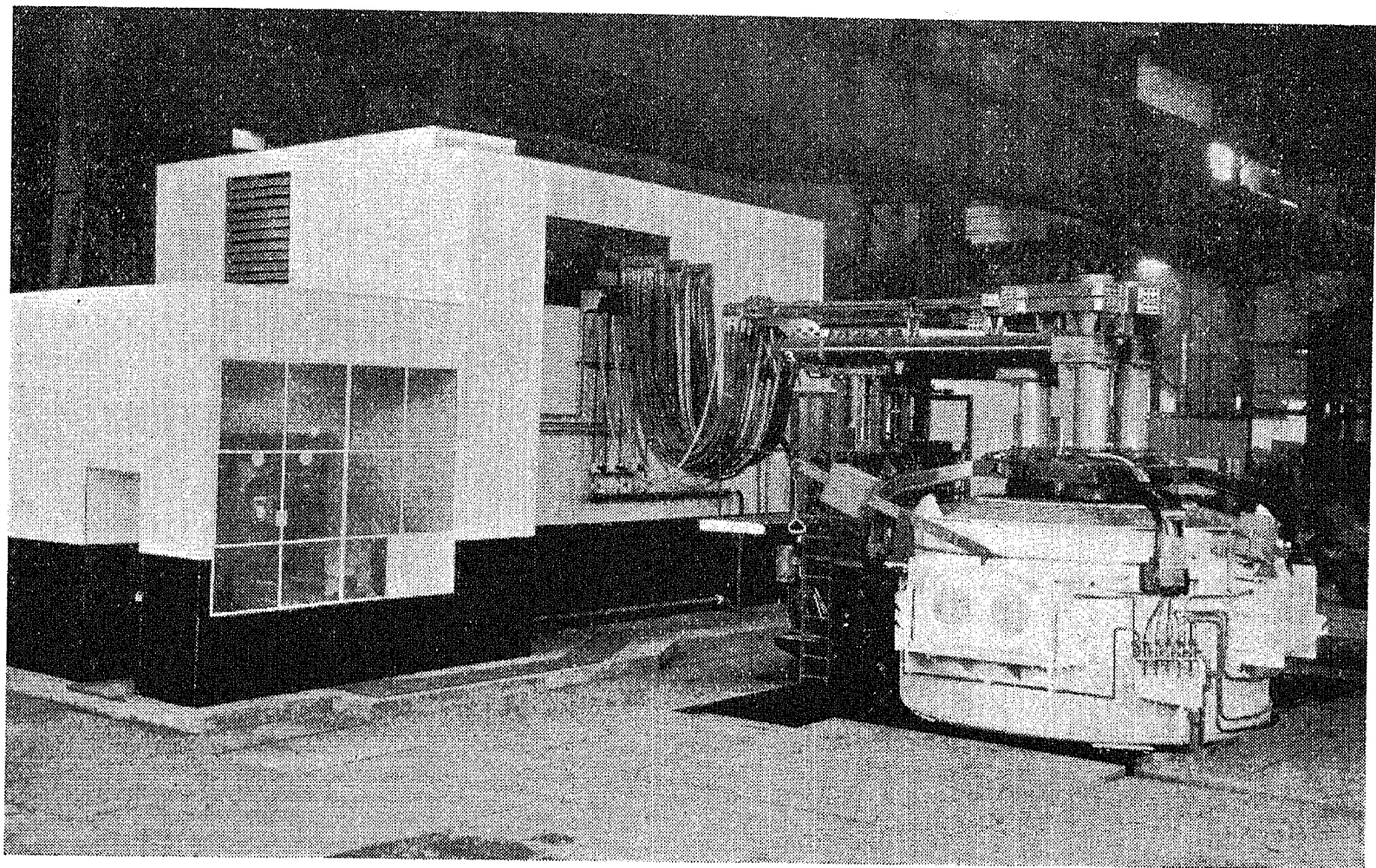


Fig. 2

The largest furnace referred to in Table 2 is of 30-ton capacity, and this represents the present convenient design limit for a 3-electrode type of furnace. By using

hollow water-cooled helical copper coil, suitably insulated electrically, against which is rammed a refractory liner, the wall thickness being from 2 in. to 4 in. The whole

Table 2

Weight of furnace charge, tons	Transformer capacity, kVA		Approx. diam. of graphite electrode, in.
	Melting	"Holding," i.e. molten charge	
0.15	150	95	2½
0.25	250	150	3
0.5	500	300	4
1.0	750	450	5-6
2.0	1 000	575	7
2.5	1 200	700	8
3.5	1 500	850	9
5.0	2 000	1 000	10
7.5	2 800	1 600	11½
10.0	3 500	2 000	12
15.0	5 000	3 000	14
20.0	6 000	3 500	15
25.0	7 000	4 000	16
30.0	8 000	4 500	16

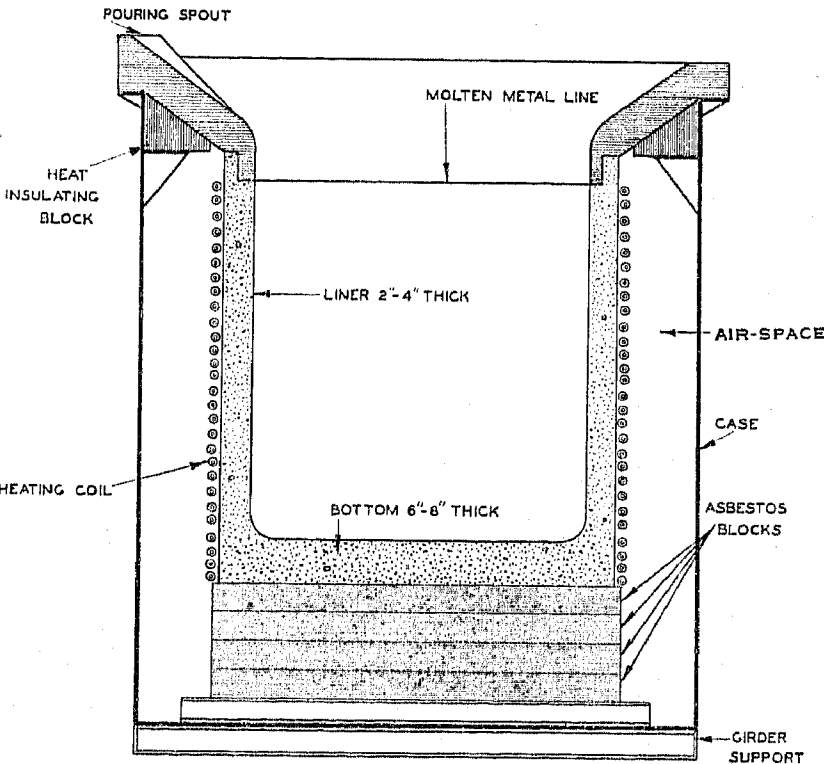


Fig. 3.—Section through high-frequency induction furnace.

multiple electrode groups, however, larger sizes can be made, and a 100-ton furnace using 6 electrodes is actually in service in America to-day.

The general form of the high frequency, or coreless, induction furnace is shown in Fig. 3. It consists of a

rests on heat insulating blocks and is surrounded by a case carefully insulated against eddy currents and made, for example, of laminated steel, with an air space between coil and case. The material to be melted is loaded in, high-frequency current is applied to the copper coil, and

currents are induced in the charge,^f causing its temperature to rise.

In the design and operation of this type of furnace it is clear that a number of factors have to be taken into account. Thus the material of the charge must be capable of being heated by high-frequency current or must be in a crucible having this property, when the heat passes to the charge by conduction; it must consist

metals or for laboratory use, employ spark-gaps giving frequencies of the order of 20 000 cycles per sec. Recently there has been a move towards radio frequencies, of the order of 300 000 and above, which are obtained by using a valve oscillator.

The majority of furnaces, however, operating at or near 2 000 cycles per sec., are fed from a motor-generator set, the motor being of the synchronous type, with phases,

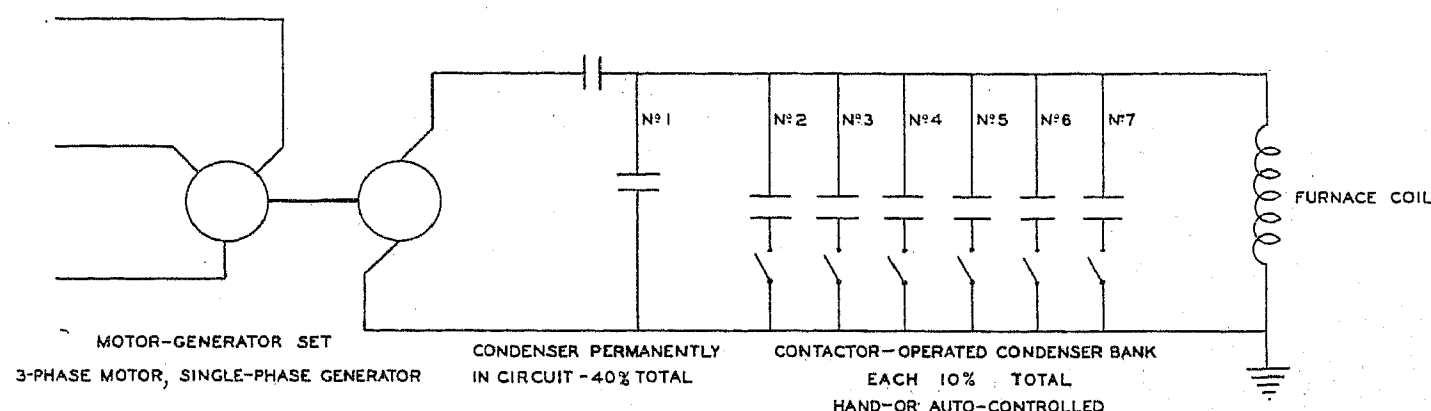


Fig. 4A.—Wiring diagram for coreless induction furnace using high-frequency motor-generator suitable for frequencies of 500–5 000 cycles per sec.

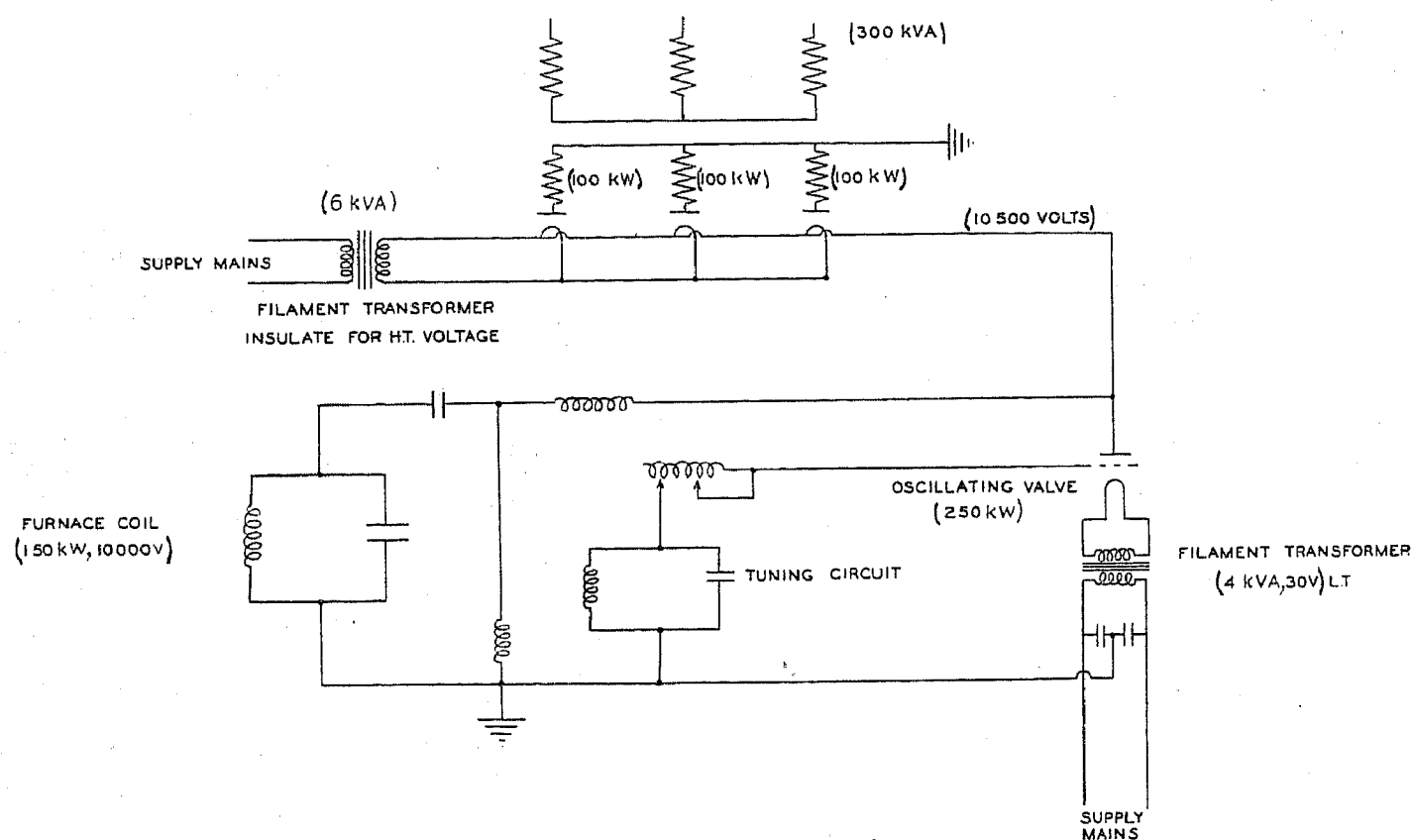


Fig. 4B.—Wiring diagram for coreless induction furnace using valve oscillator. Suitable for frequencies of 100 000 cycles per sec. or over.

Figures in brackets are appropriate values for a 5-cwt. furnace.

of lumps of a certain size, and associated with the size there is an optimum frequency. Further, the number of turns, the coil diameter, and the voltage, are inter-related. In practice a compromise between the various factors has to be reached.

At the present day the most common frequencies in commercial use are between 500 and 2 250 cycles per sec., with a tendency in this country to prefer the latter of these figures. Small furnaces, for melting precious

voltage, and frequency, suited to the supply. The generator is generally of a homopolar design. Running at 1 500 and 3 000 r.p.m., these sets have a high overall efficiency (85 %–86 % at full load) and have been found to be very satisfactory in service.

When a constant furnace frequency is employed, as is the case with motor-generators, the inductance of the secondary circuit varies throughout the melting period, resulting in wide changes of power factor. To prevent

excessive current being drawn from the motor-generator, condenser banks are placed in parallel with the furnace coil. One of these is permanently connected, while the remainder can be taken in or out of circuit by means of contactors, as shown in Fig. 4A. The contactor control is either manual by the melter, or automatic by a contact-making power-factor meter.

A valve, however, has totally different characteristics and can adapt itself to changes in electrical conditions. No power-factor correction is therefore needed, and the connection diagram is as shown in Fig. 4B.

Typical furnace sizes and motor-generator capacities are given in Table 3. As with arc furnaces, so here the

Table 3

Weight of charge, cwt.	Motor-generator capacity, kVA
5	150
10	400
20	600
40	650
100	1 500 (twin generator)

electrical rating varies for the same charge weight, but those quoted are what may be anticipated for present-day steelworks furnaces.

(2) METALLURGICAL FACTORS INFLUENCING THE DEVELOPMENT OF ELECTRIC STEELS

There exist to-day a very large number of alloy steels, most of them developed during the last 25 years, some of which present manufacturing difficulties which can only be overcome in an electric furnace.

The problems to be met with in the manufacture of alloy steels may be summarized under three main headings, one or more of which will exist in any particular case:—

(i) Oxidation of some or all of the alloy metal. This applies particularly to chromium, vanadium, tungsten, and manganese.

(ii) The necessity for keeping out gaseous and removing solid impurities, particularly sulphur and phosphorus.

(iii) A rigid control of the analysis and temperature to within narrow limits in order that the ultimate structure of the steel may be correct. This is particularly important with regard to carbon, and the presence of some alloy elements makes it very difficult to obtain ingots in which the desired structure can be derived by heat treatment.

It now becomes necessary, therefore, to see how far the electric furnace is able to reduce or overcome these difficulties.

Considering first the high-frequency furnace, this is not generally regarded as suitable for refining. Nevertheless, there is at least one large steelworks in Great Britain which uses a standard furnace of this type solely for this purpose, with excellent results (Tables 7 and 8, Furnace No. 25). Moreover, with careful supervision it has been found that in spite of the very thin walls it is possible to

get some 50 charges through before relining, corresponding to approximately 1 week's working.

On the other hand, when melting is in progress the danger of oxidation of chromium and vanadium is nil and there is no source from which carbon can be picked up. Therefore this type of furnace is very suitable for producing chrome and vanadium steels, where the raw material is either known scrap or virgin material of known composition. To this must be added the advantage that there is continuous natural circulation in the bath caused by the electromagnetic forces set up by the energizing coil—the degree of circulation is a function of the frequency.

These furnaces are also particularly suitable for intermittent operation, as they have a relatively low heat-storage capacity.

There are two general disadvantages to this type of furnace which should be pointed out. As yet it has not been built for capacities larger than 8 tons (5–6 tons in this country), and it is expensive in initial cost owing to the extensive electrical equipment needed; this latter defect is partly overcome by having two furnace bodies operating off the same electrical plant and so keeping it in continuous operation. Summarizing, therefore, it may be said that these furnaces have as:—

Advantages.—(a) Absence of oxidizing atmosphere. (b) No carbon pick-up. (c) Good natural mixing of bath. (d) Suitability for intermittent operation. (e) High temperature obtainable.

Disadvantages.—(a) Limited capacity. (b) Inability to refine easily, necessitating raw materials of known composition. (c) High capital cost.

Referring now to the arc furnace; this has been the prime cause of the development of electric steel, since an extremely accurate analysis can be obtained with it. In refining there are two distinct stages:—

(a) *Formation of black slag, or oxidizing.*—This is achieved by adding iron ore or mill scale, and lime, when manganese, silicon, carbon, and phosphorus are removed. Unfortunately during this stage there will be a tendency to remove the easily oxidized metals chromium and vanadium; skilled operatives can, however, recover a considerable proportion of the chromium present in the slag.

(b) *Formation of white slag, or de-oxidizing.*—This stage is peculiar to the electric process and consists in adding de-oxidizing agents, such as ferro-silicon or ferro-manganese, with fluorspar, carbon, and lime. In this way all oxides are removed together with sulphur, and the bath is degassed. During this stage any alloying elements which may be required are added.

These furnaces are capable of large-scale production, while their initial cost is not excessive. Where certain flexibility in the carbon content is allowed the cheaper amorphous electrodes are used, but in the majority of cases graphite is preferred as with these there need be no carbon pick-up in the bath.

Circulation is confined to relatively small areas near the arc, and therefore hand rabbling or stirring has to be resorted to to keep the temperature of the bath even and the materials properly mixed. Further, the natural heat capacity of the furnace is high and it should therefore be kept in production for as long periods as possible.

Summarizing, it may be said that these furnaces have as:—

Advantages.—(a) Ability to produce from relatively poor raw materials a steel having a rigid analysis. (b) Good capacity. (c) Reasonable cost. (d) High temperature obtainable.

Disadvantages.—(a) Tendency to oxidize out chromium and vanadium. (b) Indifferent mixing of the bath. (c) Unsuitability for intermittent operation. (d) Certain amount of carbon pick-up; small with graphite electrodes.

(3) ELECTRICITY CONSUMPTION, AND ITS INFLUENCE ON THE COST OF ELECTRIC STEEL

In order to interpret correctly electricity consumption figures it is necessary to consider the various ways in which an electric furnace can be used. These are:—

(a) Melting only.

To melt 1 ton of steel the theoretical heat consumption is as follows:—

Sensible heat at
1 500° C. = 0.162 × 1 500 × 1 000
= 243 000 kg. cal. = 962 500 B.Th.U.
Latent heat* = 49 400 kg. cal. = 195 500 B.Th.U.
Total heat = 292 400 kg. cal. = 1 158 000 B.Th.U.
The equivalent electricity consumption is therefore
1 158 000 ÷ 3 412 = 340 units.

In practice it has been found that, with a modern furnace, arc melting requires 540 to 620 units per ton, i.e. the overall efficiency is 63 % to 55 %, while h.f. melting requires 600 to 710 units per ton, i.e. the overall efficiency is 57 % to 48 %. Broadly speaking, the difference in efficiency between the two methods lies in the necessity for having a motor-generator set between the supply and the furnace in the case of the h.f. type, the peak overall efficiency of which will be about 85 % to 86 %.

Table 4
HEAT BALANCES OF ELECTRIC FURNACES WHEN MELTING

Item	Arc furnace				H.F. induction furnace			
	Maximum efficiency		Minimum efficiency		Maximum efficiency		Minimum efficiency	
	Units per ton	%	Units per ton	%	Units per ton	%	Units per ton	%
1. Effective work	340	63	340	55	340	57	340	48
2. Cooling water	16	3	25	4	15	2.5	43	6
3. Heat in gases	22	4	37	6	—	—	—	—
4. Conduction and radiation ..	114	21	156	25	112	18.5	142	20
5. Electrical losses	48	9	62	10	133	22	185	26
Total	540	100	620	100	600	100	710	100

(b) The cold-charge refining process, which is carried out in four distinct stages: (i) Melting the charge. (ii) Forming the black slag, or oxidizing. (iii) Forming the white slag, or de-oxidizing. (iv) Tapping and re-charging.

(c) The hot-charge refining process, also known as duplexing; this is similar to method (b) above except that the melting stage is omitted, thus reducing the energy consumption by the amount required for that purpose. Further, with careful work prior to the introduction of the metal into the electric furnace the oxidizing period may be reduced, or even avoided entirely.

The metal for the bath is usually derived from an open-hearth or bessemer furnace; the former being preferred, as the product of the latter is often over-oxidized and great difficulty may be experienced in de-oxidizing.

(d) Superheating. Use is made of the very high temperatures that can be obtained in an electric furnace to raise the temperature of the molten charge to about 2 000° C. and thus obtain fine, sharp castings. This is of particular value in relation to some grades of cast iron.

The approximate heat balance for both types of furnace under the limiting conditions set out above may be summarized as shown in Table 4.

The principal factors governing the electricity consumption per ton when melting are:—

(a) Capacity of furnace: parasitic losses—particularly conduction and radiation—will be a smaller proportion of the consumption per ton the larger the furnace.

(b) Cycle time: the shorter the melting and recharging time the smaller will be the effect of the continuing losses, i.e. the lower will be practically the whole of Items 2 and 3 in Table 4, together with a large proportion of Item 5 and part of Item 4.

(c) The continuity or otherwise of operation: as has already been pointed out, long periods of idleness will increase the average consumption owing to losses from the body of the furnace.

(d) The state of repair of the furnace: a furnace which is in poor condition will have heavier losses, generally, than a well-kept furnace.

Of the above factors, (d) and, to a limited extent, (b)

* According to Wuest.

Table 5

ELECTRIC ARC FURNACES INSTALLED IN STEELWORKS: SUMMARY OF PRINCIPAL FURNACE DATA

Furnace No.	Capacity, tons	Rating, kVA	Rating, kVA per ton	Maximum l.t. volts	Electrode control	Added* reactance, %	Electrodes	
							Size and material	Consumption, lb. per ton melted
1	3.5	750	215	100	Electric	30	10 in., graphite	11
2	3	900	300	84	Electric	10	8 in., graphite	18
3	0.75	450	600	84	Hand	10	6 in., graphite	18
4	7	1 200	170	80	Electric	10	12 in., graphite	16
5	1.75	600	340	84	Hand	10	8 in., graphite	18
6	15	3 500	230	210	Electric	35	12 in., graphite	18
7	4	1 500	375	185	Electric	35	9 in., graphite	16
8	15	4 000	267	180	Hydraulic	25	14 in., graphite	11
9	10	3 500	350	200	Electric	30	20 in., carbon	30
10	8	3 500	440	200	Electric	35	12 in., graphite	18
11	10	4 000	400	183	Electric	30	20 in., carbon	37
12	10	3 500	350	200	Electric	35	12 in., graphite	16
13	30	6 000	200	200	Electric	30	16 in., graphite	14
14	12	3 600	300	220	Electric	40	12 in., graphite	15
15	5	1 700	340	180	Electric	25	9 in., graphite	14
16	30	5 400	170	180	Electric	30	16 in., graphite	15.5
17	3	2 500	830	160	Electric	10	8 in., graphite	15
18	1.5	750	500	75	Hand	5	6 in., graphite	40†
19	0.6	400	660	75	Hand	5	5 in., graphite	30†
20	2	1 500	750	180	Hydraulic	10	8 in., graphite	16

* Percentage voltage-drop at rated current.

† Melting nickel.

Table 6

ELECTRIC ARC FURNACES INSTALLED IN STEELWORKS: SUMMARY OF OPERATING DATA

Furnace No.	Capacity, tons	Melting time, hr.	Refining time, hr.	Tap and recharge time, hr.	Total cycle time, hr.	Maximum demand, kW	Units per cycle	Units per annum, millions	Annual load factor, %	Melting units per ton	Melting efficiency (340 units per ton = 100 %)	Total units per ton	Refining units per ton
1	3.5	3	1	1	5	750	2 560	3.5	52.5	620	55	730	110
2	3	2	2	$1\frac{1}{2}$	$4\frac{1}{2}$	950	2 700	4.1	48.5	630	54	900	270
3	0.75	$1\frac{1}{4}$	—	$1\frac{1}{2}$	$1\frac{3}{4}$	500	560	2.0	46	750	45.5	750	—
4	7	$3\frac{1}{2}$	$3\frac{1}{2}$	1	8	1 450	6 300	20.2*	39.5	720	47	900	180
5	1.75	$2\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	4	700	1 470	2.4	38	690	49.5	840	150
6	15	3	$3\frac{1}{2}$	1	$7\frac{1}{2}$	3 500	12 150	11.6	37.5	600	57	810	210
7	4	$1\frac{3}{4}$	2	$1\frac{1}{4}$	5	1 500	2 800	4.2	32	600	57	700	100
8	15	$2\frac{1}{2}$	4	$1\frac{1}{2}$	7	3 500	9 750	9.8	32	540	63	650	110
9	10	$3\frac{1}{2}$	$3\frac{1}{2}$	2	9	3 500	10 500	15.8†	25.5	900	38	1 050	150
10	8	$1\frac{1}{2}$	$5\frac{1}{2}$	1	8	3 500	7 200	7.8	25	650	52.5	900	250
11	10	2	$3\frac{1}{2}$	$1\frac{1}{2}$	7	4 000	8 200	8.6	24.5	600	57	820	220
12	10	2	3	1	6	3 500	7 500	15.0‡	24.5	600	57	750	150
13	30	$5\frac{1}{2}$	$5\frac{1}{2}$	1	12	6 000	24 000	12.0	23	683	50	800	117
14	12	$2\frac{1}{2}$	5	1	$8\frac{1}{2}$	3 600	8 640	7.3	23	620	55	720	100
15	5	$1\frac{1}{2}$	$5\frac{1}{2}$	1	8	1 800	4 500	3.6	23	550	62	900	350
16	30	4	$4\frac{1}{2}$	1	$9\frac{1}{2}$	5 400	21 300	9.5	20	600	57	710	110
17§	3	$1\frac{1}{2}$	—	$1\frac{1}{2}$	2	2 500	2 820	2.7	12	940	36	940	—
18§	1.5	2	—	$1\frac{1}{2}$	$2\frac{1}{2}$	700	1 215	0.7	11	810	42	810	—
19§	0.6	$1\frac{1}{2}$	—	$1\frac{1}{2}$	2	390	480	0.3	7.5	800	42.5	800	—
20§	2	$1\frac{1}{2}$	—	$1\frac{1}{2}$	2	1 600	1 530	0.8	6	765	44.5	765	—

* Total consumption for 4 similar furnaces.

† Total consumption for 2 similar furnaces.

‡ Total consumption for 2 similar furnaces.

§ Operate on day shift only.

are within the control of the melter. While he cannot reduce the actual melting time below a certain limit, dependent on the transformer capacity available, he is able to see that the charge is arranged in the furnace so as to expose the material in the most efficacious manner to the heating influence of the electricity, and he has considerable power to avoid undue delays in effecting between-charge repairs and in recharging the furnace. General repairs to the furnace are clearly entirely within the control of the foreman, and considerable reduction in the losses can be made by ensuring that the equipment is kept in good condition.

How intermittent operation affects consumption can best be illustrated by two cases which came to the author's notice. An induction furnace, starting from cold, was found to have a consumption per ton which was about 12½ % greater than that recorded during the 5th consecutive melt. In the other case a 5-ton arc furnace was operated on day shift only, i.e. for 8 hours out of the 24, and 4 melts were obtained. The consumption per ton during the first melt was 35 % above that of the final melt, and over 15 % above the day's average consumption.

The cycle time of the melt will depend very largely

Table 7
ELECTRIC HIGH-FREQUENCY INDUCTION FURNACES INSTALLED IN STEELWORKS: SUMMARY OF PRINCIPAL FURNACE DATA

Furnace No.	Capacity, cwt.	Electrical rating, kVA	Rating, kVA per ton	Voltage	Frequency, cycles per sec.	Condenser control
1	5	150	600	1 500	2 200	Hand
2	10	200	400	1 800	2 220	Automatic
3	15	650	870	2 000	500	Automatic
4	10	400	800	1 500	2 250	Automatic
5	40	650	325	1 250	1 500	Automatic
6	5	150	600	1 000	500	Automatic
7	10	150	300	1 200	2 200	Hand
8	20	{ 400 kVA for 20 cwt. or (10 + 5 + 1) cwt. bodies }	—	1 000	1 500	Automatic
9	10		400	1 000	1 500	Automatic
10	5		—	1 000	1 500	Automatic
11	1		—	1 000	1 500	Automatic
12	100	1 500	300	2 700	1 000	Automatic
13	10	150	300	1 000	1 000	Automatic
14	40	625	315	1 500	1 125	Automatic
15	5	150	600	1 000	2 000	Automatic
16	20	200	200	1 500	2 220	Automatic
17	5	200	800	1 500	2 250	Automatic
18	4	150	750	1 200	2 200	Hand
19	5	200	800	1 500	2 200	Automatic
20	100	625 or 1 250	125 or 250	1 500 or 3 000	1 125	Automatic
21	10	350	700	1 200	1 500	Automatic
22	4	175	875	1 000	1 000	Automatic
23	10	400	800	1 000	1 000	Hand
24	10	150	300	1 000	1 000	Hand
25	100	625	125	1 500	1 125	Automatic

Once the duty of the furnace has been decided on, it is a relatively simple matter to determine the appropriate capacity, though it will sometimes be necessary to effect a compromise between size and continuity of operation; and on the whole it is preferable to keep a small arc furnace operating continuously rather than to have a large furnace operating intermittently. Size is of greater importance than continuity of operation, where the two conflict in the case of the induction furnace; this is not only because the heat loss from the body is of less influence but also because, during operation, the motor-generator set is almost invariably kept running continuously and the light-load losses tend to become very pronounced.

on the transformer capacity available, and here numerous factors must be taken into account. The form of the electricity tariff will have a bearing on the subject; this is, however, discussed below. In general, the melting time of arc furnaces is kept between 1 hour and 2 or 2½ hours, with a preference for about 1½ hours in most sizes commonly met with. An induction furnace melting-time varies from about ¾ hour to 2½ hours, with 1 hour as a common time for sizes up to about 3 tons, but increasing in the case of a very large (8 ton) furnace to as much as 3 hours. For either type of furnace a short melting time implies a large power input, which, in the case of the induction type, involves heavy capital cost and difficulties in designing the high-frequency generator.

The design of the transformer for arc furnaces presents no very special difficulties, but during the refining period—if any—the power input falls considerably and it then becomes necessary to balance rapid melt against high initial cost and low utility factor.

When considering refining, no generalities can be stated since the consumption will vary with the quality of the original material, the degree of accuracy of analysis required, and the ease or difficulty experienced with each melt (even furnaces can be "temperamental"). A very rigid analysis, involving a low carbon, phosphorus, and sulphur content, may require as much as 350 units

Further, since the losses are essentially proportional to the running time, the only way of reducing consumption would seem to be to improve the furnace-man's skill. Some indication of results that may be expected in practice are shown in Tables 5 and 6 for arc furnaces and in Tables 7 and 8 for induction furnaces. These Tables show clearly the wide range of consumptions met with.

Supply Costs

Electricity supply authorities have two common methods of charging: a flat rate per unit, or a two-part

Table 8

ELECTRIC HIGH-FREQUENCY INDUCTION FURNACES INSTALLED IN STEELWORKS: SUMMARY OF OPERATING DATA

Furnace No.	Capacity, cwt.	Melting time, hr.	Tap and recharge time, hr.	Total cycle time, hr.	Maximum demand, kW	Units per cycle	Units per annum, millions	Annual load factor, %	Units per ton	Melting efficiency (340 units per ton = 100 %)
1	5	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	160	168	0.9	64	670	51
2	10	2 $\frac{1}{4}$	$\frac{1}{4}$	2 $\frac{1}{2}$	220	358	1.2	62.5	715	47.5
3	15	1	$\frac{1}{4}$	1 $\frac{1}{4}$	650	525	3.5	61.5	700	48.5
4	10	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	300	300	1.6	61.0	600	57
5	40	2	$\frac{1}{4}$	2 $\frac{1}{4}$	750	1 280	4.0	61.0	640	53
6	5	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	150	165	0.8	61.0	660	51.5
7	10	3 $\frac{1}{4}$	$\frac{1}{4}$	3 $\frac{1}{2}$	150	400	0.8	61.0	800	42.5
8	20	1 $\frac{3}{4}$	$\frac{1}{4}$	2	400	625	1.1	61.0	625	54.5
9	10	1 $\frac{3}{4}$	$\frac{1}{4}$	2	400	570	1.0	60.5	715	47.5
10	5									
11	1									
12	100	2 $\frac{1}{2}$	$\frac{1}{2}$	3	1 500	3 000	8.0	60.5	600	57
13	10	2 $\frac{3}{4}$	$\frac{1}{4}$	3	175	400	0.9	60.5	800	42.5
14	40	2	$\frac{1}{4}$	2 $\frac{1}{2}$	625	1 300	3.25	59.5	650	52.5
15	5	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	175	175	0.9	59.0	700	48.5
16	20	4 $\frac{3}{4}$	$\frac{1}{4}$	5	180	650	0.9	57.0	650	52.5
17	5	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	160	150	0.8	57.0	600	57.0
18	4	2	$\frac{1}{4}$	2 $\frac{1}{4}$	150	200	0.7	57.0	1 000	34.0
19	5	50 min.	10 min.	1	200	170	1.0	57.0	680	50.0
20	100	6	$\frac{1}{2}$	7 $\frac{1}{2}$	625	3 750	3.0	55.0	750	45.5
		3	$\frac{1}{2}$	3 $\frac{1}{2}$	1 250	3 250	—	—	650	52.5
21	10	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	350	325	1.6	52.5	650	52.5
22	4	1	$\frac{1}{4}$	1 $\frac{1}{4}$	175	140	0.73	47.5	700	48.5
23*	10	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	400	365	0.7	19	730	46.5
24*	10	2 $\frac{3}{4}$	$\frac{1}{4}$	3	150	365	0.2	15.5	730	46.5
25†	100	1 $\frac{1}{4}$	$\frac{1}{4}$	1 $\frac{1}{2}$	625	875	2.1	38.0	175	—

* These furnaces are working day shifts of 44 hours per week only.

† The particulars of this furnace refer to refining of open-hearth steel charge, hence the poor load factor.

There is an idling time of 1 $\frac{1}{4}$ hours per cycle due to waiting for the next open-hearth

per ton, even when one starts with good-quality raw materials, while in other cases the consumption may fall to 100 units per ton. The approximate division of the energy is probably as follows: Effective work, 36 %; cooling water, 7 $\frac{1}{2}$ %; heat in gases, 7 $\frac{1}{2}$ %; conduction and radiation, 42 %; electrical losses, 7 %.

While in general the same factors contribute to the efficiency when either melting or refining, nevertheless a reduction in the refining time cannot be achieved by applying heavy power inputs; in fact, such a procedure would produce very inferior steel with characteristics worse than those of the ordinary open-hearth quality.

tariff consisting of a kW or kVA charge and a unit charge. For the purposes of this discussion it will be assumed that the tariffs available are: Flat rate, 0.55d. per unit; two-part, £3 per kW of maximum demand per annum and 0.25d. per unit. The two tariffs are plotted in Fig. 5, from which it will be seen that up to a load factor of 27 $\frac{1}{2}$ % the flat rate is to be preferred, and above that load factor the two-part tariff.

Some idea of how the cost of the steel can be influenced by the melting procedure is obtained from Fig. 6, which gives the electrical data for two successive melts in the same furnace. It can be assumed that the unit con-

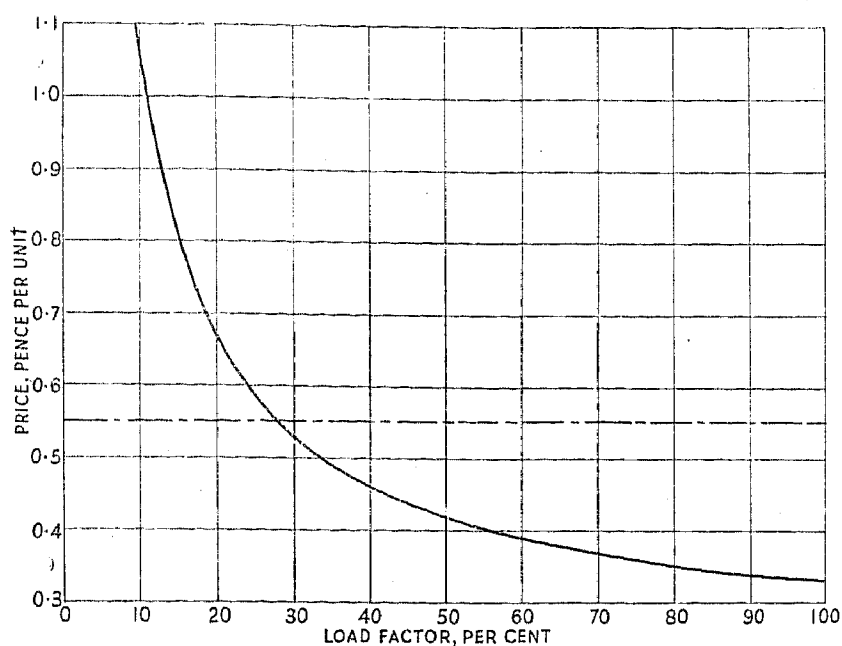


Fig. 5.—Comparison between two-part tariff and flat rate, at various load factors.

— £3 per kW per annum and 0.25d. per unit.
 - - - 0.55d. per unit.

assumptions are the minimum necessary. The total melting time and the values of average melting consumption per ton are practically identical. But the maximum demand metered over half an hour is 3 600 kW in the first case and 4 400 kW in the second. As a consequence the running-hour load factor is $45\frac{1}{2}\%$ in the case of the second melt, whereas if the previous maximum demand had not been exceeded it would have been $55\frac{1}{2}\%$. The tariff curve (Fig. 5) shows that with these load factors the values of average cost per unit, on the two-part tariff, would be 0.431d. and 0.398d. respectively. The difference of 0.033d. per unit is equivalent to about 2s. per ton of steel on a consumption of 678 units per ton.

Fig. 6 also shows the influence of the refining consumption and time on the cost of steel. The deductions are summarized in Table 9, where Case I is the first melt in Fig. 6; Case IIa the second melt, and with the actual demand recorded; and Case IIb is the same as Case IIa, except that the maximum demand is assumed to be as in Case I. On the true figures the difference in cost as between Case I and Case IIa is evidently in favour of Case IIa by a small amount, owing to the very much

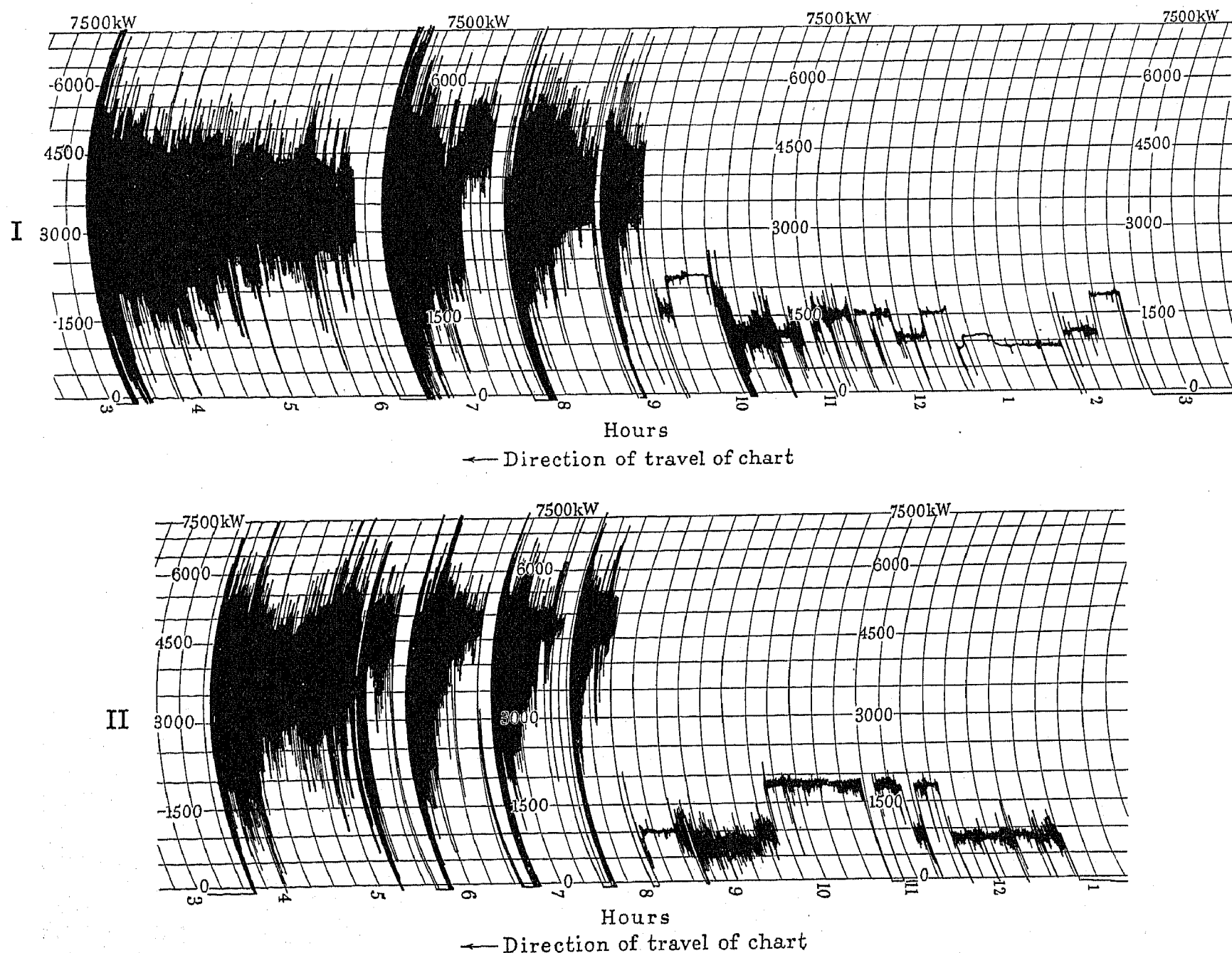


Fig. 6

I. Units used for melting, 20 900; units used for refining, 4 600; total, 25 500; maximum demand, 3 600 kW. Input, 72 125 lb.
 II. Units used for melting, 20 400; units used for refining, 1 400; total, 21 800; maximum demand, 4 400 kW. Input, 72 043 lb.

smaller consumption when refining, while with the same maximum demand in both cases there would be an advantage of nearly 4s. per ton in favour of Case II*b*.

Referring now to Tables 6 and 8, the results have been tabulated in descending magnitude of annual load factor. Table 6 indicates that of the 20 arc-furnace installations considered, 12—or over one-half—operate at apparent load factors of less than 27½ %. In other words, in these 12 cases the hypothetical flat rate is to be preferred while in the remaining cases the two-part tariff shows to advantage. Table 8, on the other hand, indicates that with two exceptions the induction furnace (a melting furnace only) operates at a load factor which would make the two-part tariff preferable.

Where there are a number of furnaces in use in the same works there will undoubtedly be some diversity

(4) THE FURNACE LOAD FROM THE SUPPLY AUTHORITIES' POINT OF VIEW

An electricity supply authority is confronted with two main questions when asked to consider supplying energy for a particular purpose: how best to frame the tariff so as to attract the consumer and at the same time not involve the undertaking in a loss; and what effect, if any, the load will have on the other consumers.

In regard to the first query, this is so much a matter for individual consideration that no attempt can be made here to supply an answer. It may be recalled, however, that a melting and refining furnace has a poor load factor and therefore the supply authority will generally consider a two-part tariff safer, although a flat rate is generally preferred by the consumer.

The question of the effect of the furnace load on other

Table 9
COSTS PER TON FOR MELTING AND REFINING STEEL UNDER VARYING CONDITIONS

Case	Load factor	Price on 2-part tariff	Melting		Refining		Total	
			Units per ton	Cost	Units per ton	Cost	Units per ton	Cost
I	per cent 57	pence per unit 0·394	650	£ 1·07	143	£ 0·23	793	£ 1·30
II <i>a</i>	45·5	0·431	635	1·14	43	0·08	678	1·22
II <i>b</i>	55·5	0·398	635	1·05	43	0·07	678	1·12

between the maximum kilowatt demands. In one works there were installed the following furnaces:—

Arc	..	..	..	{	4 × 1 200 kW
					1 × 1 500 kW
					1 × 3 500 kW
High-frequency induction				{	1 × 650 kW
					1 × 150 kW
Total	..	..			10 600 kW

The apparent load factor in a particular year was 28 %, though the actual load factor was about 45 %, and therefore the diversity must have been 60 % to 65 %. No rule can be laid down as to the calculation of diversity since, naturally, the number of furnaces, their duty, and the steps taken to “stagger” their operation or otherwise reduce the maximum demand, must be taken into account.

Various attempts have been made by large furnace users to overcome the difficulty of poor load factor. Most of these efforts have been directed towards preventing the simultaneous operation of the furnaces on melting load. Where trade is slack such a method can often be successfully adopted, but in most cases the motto of a steelworks seems to be “maximum output possible.” As a consequence any attempt by the electrical engineer to interfere with works output is discouraged. The only remedy left, therefore (which is also disliked), is to de-rate the transformer and increase the melting time, a device that may prove advantageous on the whole even though rejected when first suggested.

consumers is susceptible of fuller treatment. The high-frequency furnace would appear to be a very desirable load from every point of view. Individual units are only infrequently stopped and started; the motor of the motor-generator can be over-excited so as to correct the works (and thus the system) power factor; and the load factor during operation is good. Further, no severe fluctuations of power are recorded. A typical power input curve for a ½-ton furnace is shown in Fig. 7. It will be noted that about 10 minutes after the beginning of the melt the consumption falls to a minimum and then rises again; at the point of minimum consumption a temperature of about 750°–800° C. has been reached, and the charge undergoes a structural change—probably from the ferromagnetic to the paramagnetic state.

The fundamental method of operation makes the arc furnace a difficult load to supply. In Fig. 8 is shown a typical load chart for a 4-ton foundry (i.e. melting) furnace. The violent load fluctuations recorded are due to the repeated striking of the arc on one or more phases, until the charge has melted sufficiently to enable the arc to burn steadily; normally this occurs about half-way through the melt. Although the furnace transformer in this case is rated at 1 500 kVA it will be seen that the upper value of the load fluctuations is not recorded, owing to the limitations of the chart. Actually, on heavily damped instruments, instantaneous load swings of 1 000–2 000 kW have been noted on this furnace. Such load fluctuations are liable to cause severe disturbances to other consumers, and therefore the load merits further analysis.

In Appendix 1 is given a method for readily deter-

mining the supply characteristics for maximum power to the arc, having given the voltage, reactance, and resistance of the furnace; the variable being the arc length, which alters the voltage drop across the arc, and which is treated as equivalent to a variable resistance

As a general rule it may be said that during refining a low voltage is to be preferred for metallurgical reasons. Furthermore, the power-input steps are less coarse with variable reactance, while the arc stability is greater at low powers and the likelihood of short-circuit due to

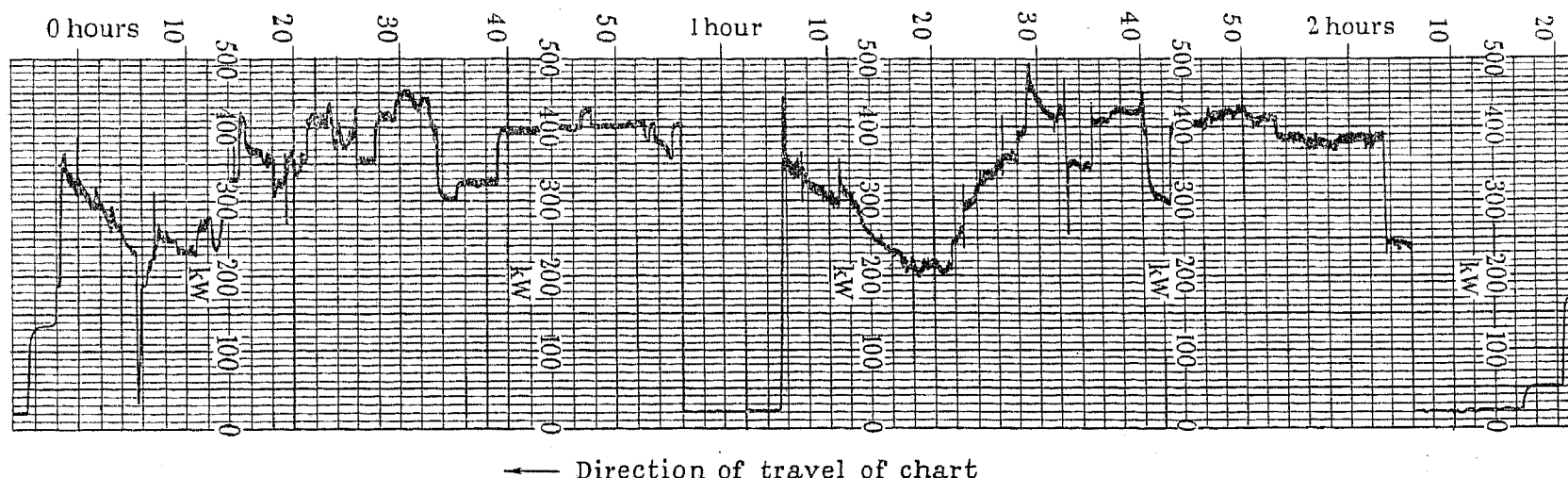


Fig. 7

in the circuit. It is universal practice to-day to add additional reactance, so chosen as to limit the maximum current taken from the mains, but also intended to stabilize the arc. The reactance thus inserted may be either fixed or fitted with tappings so as to make the total amount of reactance in circuit proportional to the arc voltage; that is to say, there are as many tappings as on the transformer. The effects of operating under these two sets of conditions is shown in Table 10, using the argument developed in Appendix 1. This Table shows that at the point of maximum arc power and with

restriking the arc is less. Therefore, the commonest practice at the present day is to have as many tappings on the reactor as there are on the transformer.

It is seldom that furnaces are worked at the point of maximum arc power, since the power factor at that point is low. Table 11 has therefore been prepared and, in conjunction with Figs. 9A, 9B, and 9C, shows what may be termed the "characteristics" of a furnace. These comprise curves of arc power, power factor, total power, and circuit kVA for various line currents. The operating position is then chosen at some point below the

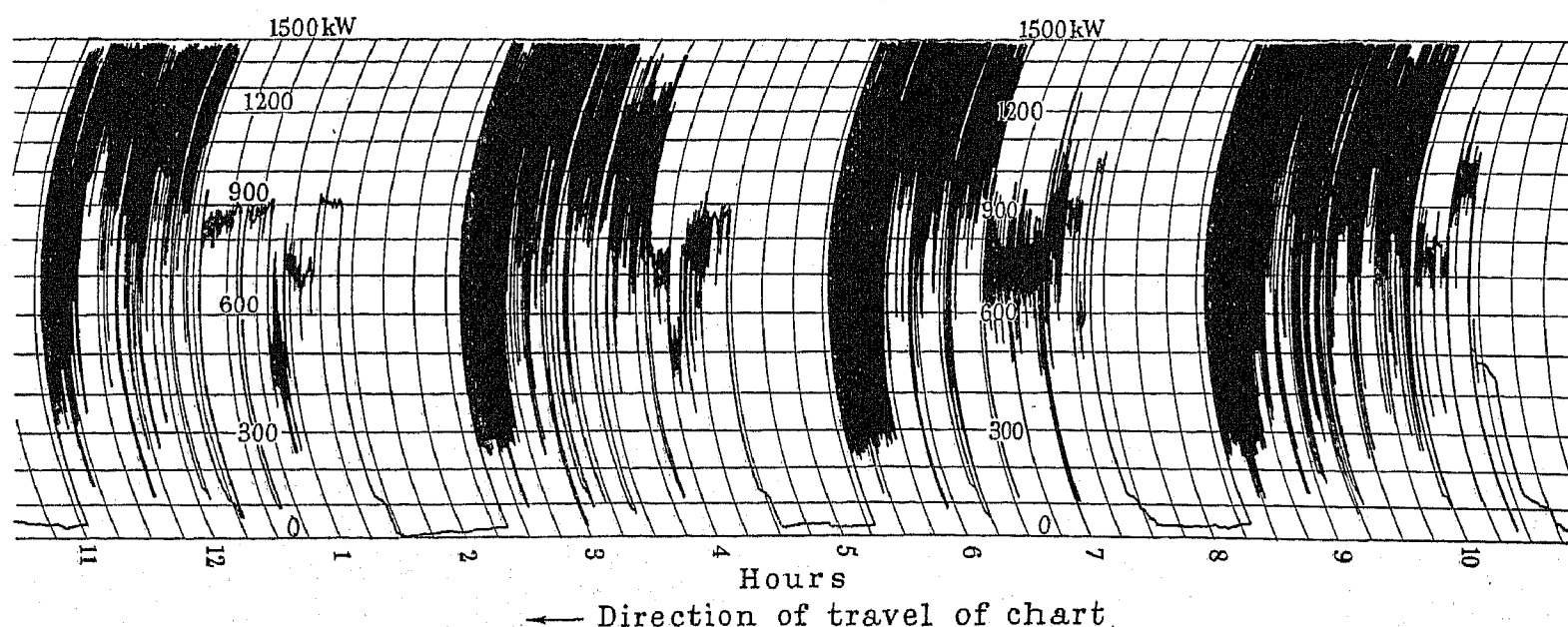


Fig. 8

constant reactance the power factor remains constant, and the arc power is proportional to the square of the voltage; whereas with a variable reactance the power factor improves at the lower voltages, while the arc power is approximately proportional to the $1\frac{1}{2}$ power of the voltage (depending of course on the value of r , the external circuit resistance).

maximum such that the desired power factor is achieved—assumed to be 0.875 in the example. This operating point is adhered to as far as practicable by the melter, no automatic restraint being imposed but a clear indication being given on the meter panel of the correct operating position for the highest voltage. Naturally, when designing the transformer it will be necessary to

take into account the possibility of the maximum arc-power position being reached.

To the supply authority the most serious difficulty is the repeated short-circuits during melting. The severest conditions are those where all three electrodes simultaneously dip into a bath of molten metal, i.e. when the equivalent resistance of the arc is zero. Such a contingency is very remote, but nevertheless must be considered. Table 11 shows that with maximum arc voltage and for the values of r and X assumed, this short-circuit current will be 35 320 amp. at a power factor of 0.2. It is usual for the supply authority to lay down that the short-circuit current shall be limited to a certain multiple of the full-load current. In the

factor at the operating point must of necessity also have dropped—to 0.7 in the example—while the arc power is now only 4 400 kW. On the other hand, the point of maximum arc power is now such that $I = 15\,800$ amp., $\cos \theta = 0.75$, and $P_a = 4\,550$. Thus the short-circuit current would be about 1.52 times the current at maximum arc power, which is approximately the same as before.

It is therefore clear (a fact that is also brought out by the formulae of Appendix 1) that indiscriminate increase of the reactance will only have a bad effect on the furnace as a whole, without assisting in any way except to reduce the short-circuit current relative to a predetermined operating current. This result can be

Table 10*

DETERMINATION OF SUPPLY CONDITIONS AT VARIOUS VOLTAGES, WITH MAXIMUM POWER SUPPLIED TO THE ARCS

(A) Reactance Constant

$$r = 0.0025 \text{ ohm.} \quad X = 0.012 \text{ ohm.} \quad z = 0.01226 \text{ ohm}$$

E		I	Arc power, P_a	Total power, P_r	$\cos \theta$
volts		amp.	kW	kW	
250 } 173 } 144 }	Star {	22 765	6 353	7 649	0.776
		15 750	3 042	3 662	0.776
		13 110	2 107	2 537	0.776
100 } 80 }	Delta {	9 105	1 016	1 224	0.776
		7 285	651	783	0.776

(B) Reactance Proportional to Voltage

$$r = 0.0025 \text{ ohm}$$

E	X	z	I	Arc power, P_a	Total power, P_r	$\cos \theta$
volts	ohm	ohm	amp.	kW	kW	
250 } 173 } 144 }	Star {	0.01200	22 765	6 353	7 649	0.776
		0.00830	21 537	4 029	5 191	0.803
		0.00691	20 727	3 158	4 232	0.819
100 } 80 }	Delta {	0.00480	18 722	1 896	2 772	0.855
		0.00384	17 205	1 356	2 096	0.880

* The symbols employed in this Table are defined in Appendix 1.

example in Table 11 the full-load current could be taken either as 17 320 amp. (that of the desired operating position) or 22 765 amp. (that at maximum arc power), and the multiples are then 2 or 1.55 respectively. It is clear, therefore, that it must be definitely established what is to be regarded as the full-load current.

To reduce the current swings, additional reactance could of course be added. The effect of this will now be shown.* Assume $E = 250$ volts, $X = 0.018$ ohm, $r = 0.0025$ ohm; then $z = 0.01817$. For the short-circuit condition we have $\cos \theta = 0.138$, $I = 24\,000$ amp. This results in the current being less than 140 % of the operating value assumed above. But we have now a worse power factor at short-circuit, and the power

* The symbols used here are defined in Appendix 1.

equally well achieved by choosing a higher operating current originally, but this necessitates, of course, a correspondingly bad power factor, as is seen from Figs. 9A, 9B, and 9C. Again, the power supplied to the arc is a function of voltage and impedance; and therefore, considering the problem of how to produce a given power input with the maximum voltage allowable, the only variable is the impedance, which in turn can only be altered by reducing the reactance, since the fixed resistance component is negligible for this argument.

Summarizing, therefore, it may be said that an arc-furnace load is such that with a good operating power factor the short-circuit current swings to be taken on the mains will be from $1\frac{1}{2}$ to 2 times full load under the worst conditions; that these swings will occur during the

Table 11

ARC-FURNACE CHARACTERISTICS: TRANSFORMER, 7 500 kVA

 $r = 0.0025 \text{ OHM}$; $z = 0.01226 \text{ OHM}$

R_a	R	$R^2 \times 10^{-4}$	$(R^2 + X^2) \times 10^{-4}$	$\sqrt{(R^2 + X^2)} \times 10^{-2}$	Current I	Arc power P_a	Total kVA P_t	Total power P_r	$\cos \theta$	Remarks
No. 1 low-voltage tap, 250 volts (line to neutral); $X, 0.012 \text{ ohm}$										
ohm	ohm	ohm	ohm		amp.	kW		kW		
0.0391	0.0416	17.309	18.749	4.330	10 000	3 910	4 330	4 160	0.961	Operating position
0.0315	0.0340	11.578	13.018	3.608	12 000	4 536	5 196	4 895	0.942	
0.0261	0.0286	8.126	9.566	3.093	14 000	5 116	6 062	5 607	0.925	
0.02175	0.02425	5.883	7.323	2.706	16 000	5 568	6 928	6 207	0.896	
0.0194	0.0219	4.810	6.250	2.500	17 320	5 820	7 500	6 570	0.875	Maximum arc-power conditions
0.0155	0.0180	3.247	4.687	2.165	20 000	6 200	8 660	7 200	0.831	
0.0137	0.0162	2.617	4.057	2.014	21 500	6 333	9 310	7 485	0.804	
0.01226	0.01476	2.178	3.618	1.902	22 765	6 353	9 857	7 649	0.776	
0.0090	0.0115	1.332	2.772	1.665	26 000	6 084	11 258	7 779	0.691	"Short-circuit" conditions
0.00725	0.00975	0.950	2.390	1.546	28 000	5 684	12 124	7 650	0.631	
0.00551	0.00801	0.642	2.082	1.443	30 000	5 059	12 990	7 209	0.555	
0.00375	0.00625	0.391	1.831	1.353	32 000	3 840	13 856	6 400	0.462	
0	0.0025	0.0625	1.503	1.226	35 320	0	15 294	3 120	0.204	
No. 5 low-voltage tap, 80 volts (line to neutral); $X, 0.012 \text{ ohm}$										
0.0421	0.0446	19.896	21.336	4.619	3 000	379	416	401	0.966	X constant
0.0300	0.0325	10.560	12.000	3.464	4 000	480	554	520	0.938	
0.0194	0.0219	4.810	6.250	2.500	5 542	596	768	673	0.875	
0.01226	0.01476	2.178	3.618	1.902	7 285	651	1 009	783	0.776	
0.0085	0.0110	1.217	2.657	1.630	8 500	614	1 178	795	0.675	Maximum arc-power conditions
0.0044	0.0069	0.481	1.921	1.386	10 000	440	1 386	690	0.498	
0	0.0025	0.0625	1.503	1.226	11 302	0	1 566	319	0.204	
No. 5 low-voltage tap, 80 volts (line to neutral); $X, 0.00384 \text{ ohm}$										
0.0108	0.0133	1.774	1.921	1.386	10 000	1 080	1 386	1 330	0.960	X proportional to volts $z = 0.00458 \text{ ohm}$
0.0084	0.0109	1.187	1.334	1.155	12 000	1 210	1 663	1 570	0.944	
0.00663	0.00913	0.833	0.980	0.990	14 000	1 299	1 940	1 789	0.922	
0.00527	0.00777	0.603	0.750	0.866	16 000	1 349	2 217	1 989	0.897	
0.00458	0.00708	0.501	0.648	0.805	17 205	1 356	2 384	2 096	0.880	Maximum arc-power conditions
0.00327	0.00577	0.333	0.480	0.693	20 000	1 308	2 771	2 308	0.833	
0.00250	0.005	0.250	0.397	0.630	22 000	1 210	3 048	2 420	0.794	
0.00181	0.00431	0.186	0.333	0.577	24 000	1 043	3 325	2 483	0.747	
0.00120	0.00370	0.137	0.284	0.533	26 000	811	3 603	2 501	0.694	"Short-circuit" conditions
0.00063	0.00313	0.098	0.245	0.495	28 000	494	3 880	2 454	0.632	
0	0.0025	0.0625	0.210	0.458	30 250	0	4 191	2 288	0.546	

Arc-furnace characteristic curves

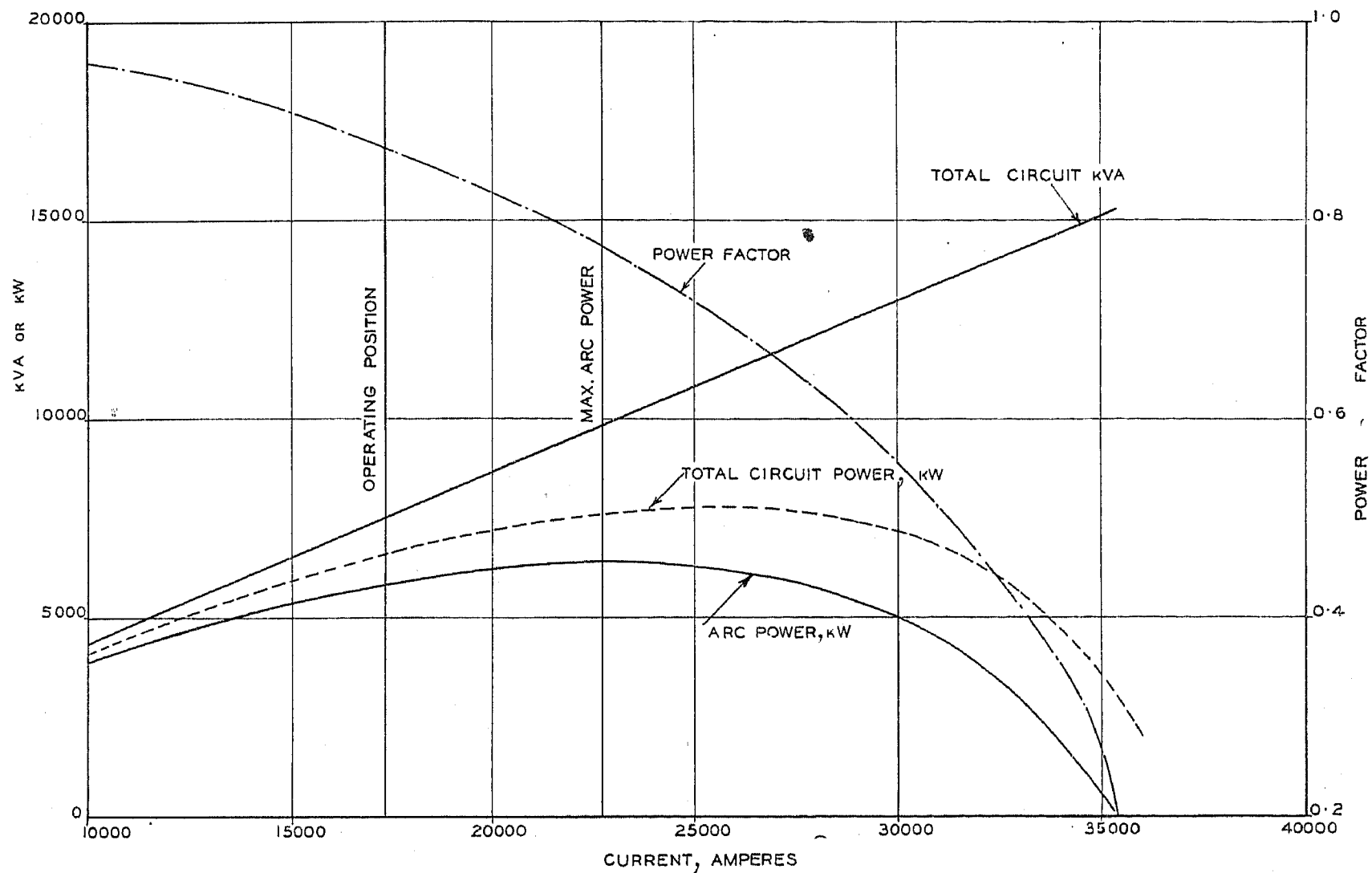


Fig. 9A

Full voltage on furnace, 250 volts line-to-neutral, $X = 0.012$ ohm.

Arc-furnace characteristic curves

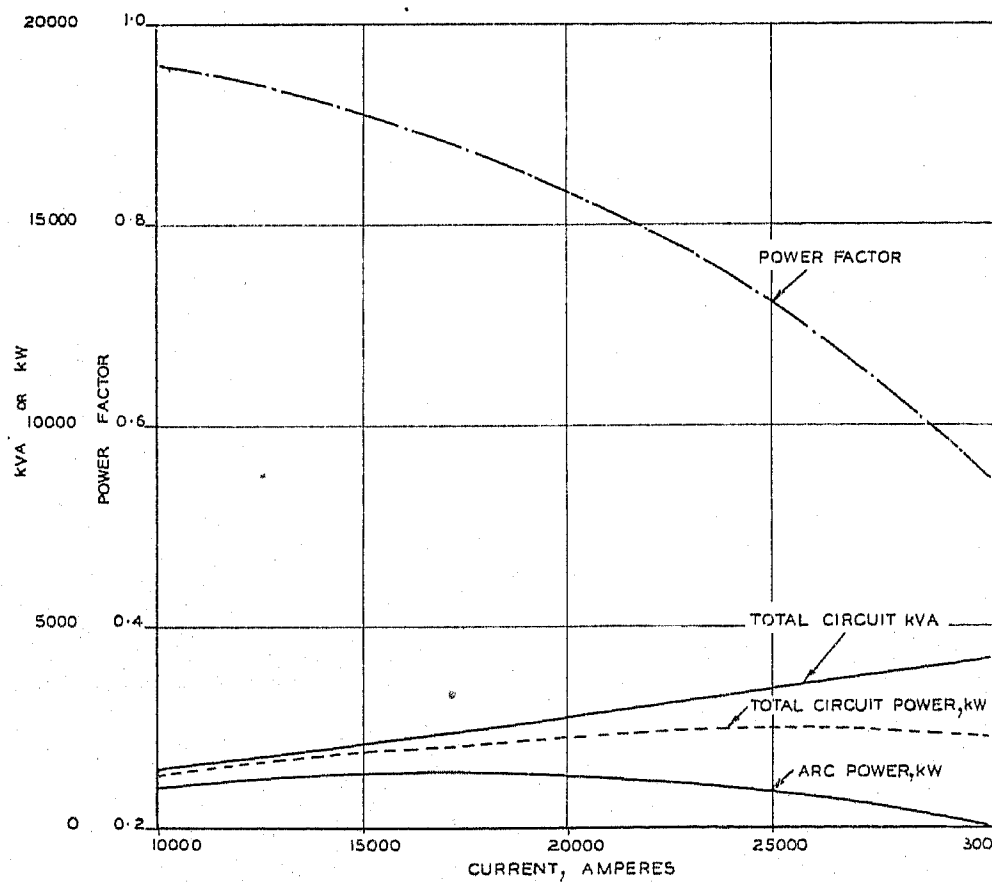


Fig. 9B

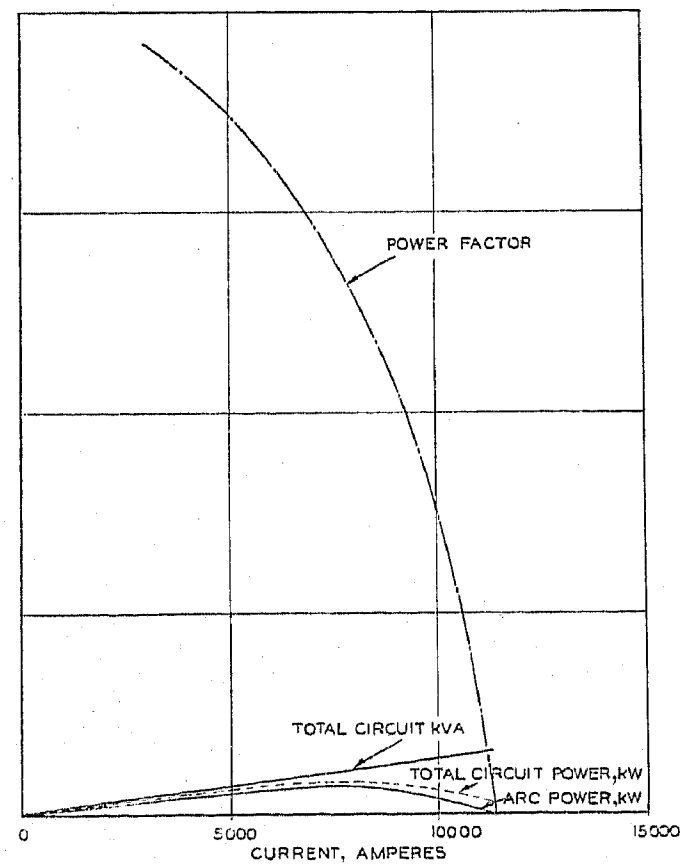
Minimum voltage on furnace, -80 volts line-to-neutral, $X = 0.00384$ ohm.

Fig. 9C

Minimum voltage on furnace, 80 volts line-to-neutral, $X = 0.012$ ohm.

SIEVEKING: ELECTRICALLY MANUFACTURED STEELS

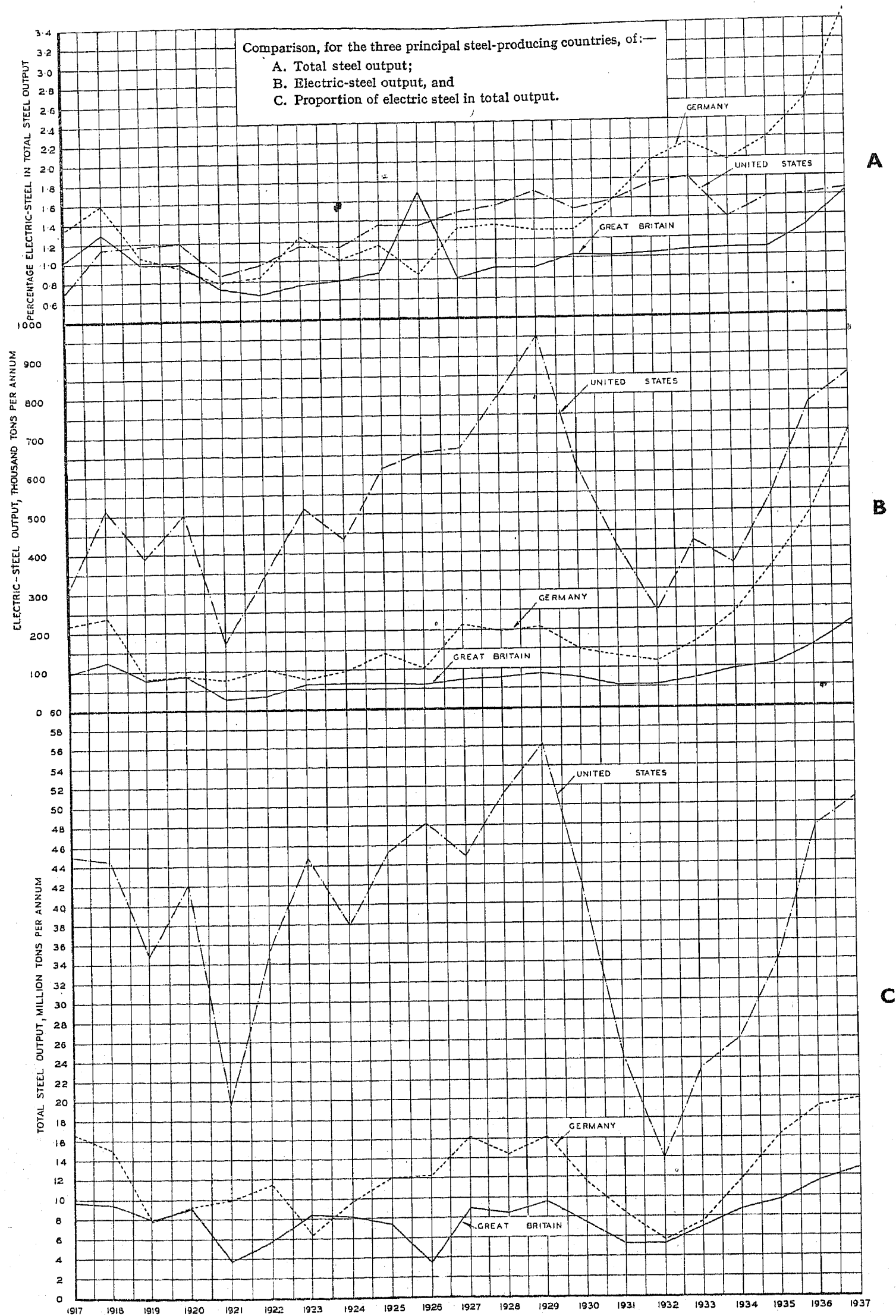


Fig. 10.—Progress in electric-steel production.

first half of the melting period; and that attempts to reduce them can only be met by reduced input to the furnace at a poorer power factor, assuming the maximum permissible voltage applied to the arc.

(5) AN OUTLINE OF THE INCREASE AND PRESENT TENDENCIES IN ELECTRIC-STEEL OUTPUT

From what has been said in Section (2) it will be realized that so far as the production of steel in this country is concerned, electrical manufacture is essentially suitable for special alloy steels, which form only a small proportion of the total output of the country.

very closely the total output; that is, the proportion is nearly constant but tends to rise during the years 1931-33, the period of world-trade depression.

(c) In Germany the fluctuations of percentage of electric steel are more marked. There is a peak in 1918, a decrease in the immediate post-War years, and a peak again in 1923, when the country suffered a financial collapse and the total output was low. Thereafter until 1930 the proportion is approximately constant. Then during the depression years and the period of rearmament there is a rapid increase, particularly in 1937. In the latter year another factor probably accounts for the large increase in both the proportion

Table 12

DIVISION OF TOTAL STEEL OUTPUT OF GREAT BRITAIN ON A PERCENTAGE BASIS BETWEEN THE PRINCIPAL PRODUCTION PROCESSES, FOR A PERIOD OF 21 YEARS

Year	Total annual output (100 per cent)	Electric steel	Open hearth	Bessemer	Electric	Other types
	million tons	thousand tons	per cent	per cent	per cent	per cent
1917	9.717	99	81.31	15.45	1.02	2.22
1918	9.539	125	82.48	13.69	1.31	2.52
1919	7.894	77	87.38	9.95	0.98	1.69
1920	9.067	89	88.02	9.09	0.98	1.91
1921	3.703	27	90.47	6.45	0.73	2.35
1922	5.881	39	90.19	7.99	0.66	1.16
1923	8.482	64	91.87	5.85	0.76	1.52
1924	8.201	65	91.16	6.28	0.79	1.77
1925	7.385	64	90.88	6.45	0.87	1.80
1926	3.596	61	91.42	4.25	1.69	2.64
1927	9.097	74	92.80	4.89	0.81	1.50
1928	8.520	78	91.92	5.59	0.92	1.57
1929	9.636	87	92.16	5.50	0.91	1.43
1930	7.326	76	93.55	3.48	1.04	1.93
1931	5.203	53	94.71	2.18	1.02	1.99
1932	5.261	55	95.06	2.13	1.04	1.77
1933	7.024	75	94.76	2.69	1.07	1.48
1934	8.850	96	94.64	2.52	1.08	1.76
1935	9.859	107	92.90	4.29	1.08	1.73
1936	11.785	153	92.25	4.78	1.30	1.67
1937	12.984	215	91.46	5.18	1.66	1.70

The effect of this is shown in Table 12, which indicates what proportions of the total output are produced by each of the major processes. To enable comparisons to be drawn with the two other principal steel-producing countries similar information is given in Table 13 for Germany, and Table 14 for the U.S.A. Fig. 10 compares the trends in electric-steel production in these countries over the 21-year period 1917-37.

Examination of Fig. 10 brings out the following interesting points.

(a) In Great Britain until 1934 the proportion of electric steel was nearly constant, with two well-marked exceptions in 1918 and 1926—the last year of the Great War and the year of the General Strike respectively. Since 1934, which corresponds to a period first of trade depression and then of rearmament, there has been a steady increase in the proportion.

(b) In the U.S.A. the electric-steel output follows

and the absolute quantity made, namely the necessity for avoiding the import of iron ore, i.e. reducing steel tonnage to the lowest possible limit.

As regards world outputs of electric steel, other conditions apply. A summary is given in Table 15 of the total steel output, electric-steel output, and ratio of the latter to the former, for the eleven principal electric-steel producing countries for the last 4 years. Since the details for 1937 are incomplete, the present discussion will be primarily concerned with the years 1934-36. It is interesting to see that in general the relative positions of the countries remain practically the same.

From Table 15 the following facts emerge:—

(a) The U.S.A., Germany, and Great Britain stand respectively first, second, and third in regard to total output, but sixth, eighth, and ninth in respect of the proportion of electric steel produced, being superior only to Luxemburg and Belgium.

Table 13

DIVISION OF TOTAL STEEL OUTPUT OF GERMANY ON A PERCENTAGE BASIS BETWEEN THE PRINCIPAL PRODUCTION PROCESSES, FOR A PERIOD OF 21 YEARS

Year	Total output (100 per cent)	Electric steel	Open hearth	Bessemer	Electric	Other types
	million tons	thousand tons	per cent	per cent	per cent	per cent
1917	16.587	220	43.91	44.90	1.33	9.86
1918	14.980	240	45.19	43.82	1.60	9.39
1919	7.847	82	57.04	37.65	1.05	4.26
1920	9.278	88	60.46	35.25	0.95	3.34
1921	9.997	79	60.50	35.61	0.79	3.10
1922	11.714	105	60.00	36.08	0.85	3.07
1923	6.305	79	64.08	31.49	1.25	3.18
1924	9.835	98	55.96	40.78	1.00	2.26
1925	12.195	140	54.26	42.15	1.15	2.44
1926	12.342	105	53.48	44.18	0.85	1.49
1927	16.311	215	54.51	42.41	1.32	1.76
1928	14.517	196	51.78	45.05	1.35	1.82
1929	16.246	209	51.51	45.51	1.29	1.69
1930	11.539	149	52.41	44.47	1.29	1.83
1931	8.292	131	57.68	38.86	1.58	1.88
1932	5.770	115	63.85	31.42	1.99	2.74
1933	7.612	165	61.10	34.51	2.17	2.22
1934	11.916	236	58.82	37.00	1.98	2.20
1935	16.447	362	53.63	41.91	2.20	2.26
1936	19.208	499	53.81	41.00	2.60	2.59
1937	19.849	700	53.70	40.10	3.52	2.68

Table 14

DIVISION OF TOTAL STEEL OUTPUT OF U.S.A. ON A PERCENTAGE BASIS BETWEEN THE PRINCIPAL PRODUCTION PROCESSES, FOR A PERIOD OF 21 YEARS

Year	Total output (100 per cent)	Electric steel	Open hearth	Electric	Bessemer and crucible
	million tons	thousand tons	per cent	per cent	per cent
1917	45.061	305	75.73	0.68	23.59
1918	44.462	512	77.47	1.15	21.38
1919	34.671	387	77.66	1.17	21.17
1920	42.133	506	77.51	1.20	21.29
1921	19.784	170	78.76	0.86	20.38
1922	35.603	346	82.34	0.97	16.69
1923	44.944	516	79.86	1.15	18.99
1924	37.932	433	83.25	1.14	15.61
1925	45.394	616	83.83	1.36	14.81
1926	48.294	652	84.24	1.35	14.41
1927	44.935	666	84.71	1.48	13.81
1928	51.544	802	85.62	1.55	12.83
1929	56.433	951	85.67	1.69	12.64
1930	40.699	613	86.17	1.50	12.33
1931	25.946	411	86.72	1.59	11.69
1932	13.681	241	87.02	1.76	11.22
1933	23.232	421	87.71	1.81	10.48
1934	26.055	361	90.30	1.39	8.31
1935	34.093	541	90.10	1.59	8.31
1936	47.768	772	91.14	1.61	7.25
1937	50.569	846	91.49	1.67	6.84

Table 15

SUMMARY OF STEEL OUTPUT FOR THE PRINCIPAL COUNTRIES OF THE WORLD (EXCLUDING RUSSIA), SHOWING PROPORTION PRODUCED ELECTRICALLY AND RELATIVE POSITION OF EACH COUNTRY

Country	Total output, million tons				Electric-steel output, thousand tons				Percentage electric steel in total output				Relative position of country as to:—											
													Total output				Electric-steel output				Percentage electric steel in total output			
	1934	1935	1936	1937	1934	1935	1936	1937	1934	1935	1936	1937	1934	1935	1936	1937	1934	1935	1936	1937				
U.S.A.	26.06	34.09	47.77	50.57	361	541	772	846	1.39	1.59	1.61	1.67	1	1	1	1	2	2	1	1				
Italy ..	1.80	2.18	1.99	2.05	455	557	591	—	25.38	25.58	29.70	—	8	7	7	8	1	1	2	—				
Germany ..	13.65	16.19	18.90	19.85	236	362	499	700	1.73	2.23	2.64	3.52	2	2	2	2	3	3	3	4				
France ..	6.08	6.18	6.60	7.80	198	246	272	316	3.26	3.98	4.13	4.05	4	4	4	4	4	4	4	3				
Sweden ..	0.85	0.88	0.96	1.09	165	186	206	254	19.42	21.18	21.48	23.28	9	11	11	11	5	5	5	1				
Japan ..	3.74	4.86	5.00	5.72	149	173	190	—	4.00	3.56	3.80	—	5	5	5	5	6	6	6	—				
Great Britain ..	8.85	9.86	11.78	12.98	96	107	153	215	1.08	1.08	1.30	1.65	3	3	3	3	7	7	7	7				
Canada ..	0.74	0.92	1.08	1.35	23	33	35	56	3.11	3.59	3.24	4.15	11	10	10	10	8	8	8	9				
Poland ..	0.84	0.93	1.11	1.43	17	20	20	25	2.02	2.15	1.80	1.75	10	9	9	9	9	9	9	2				
Belgium ..	2.90	2.98	3.13	3.81	8	10	10	43	0.28	0.34	0.32	1.13	6	6	6	6	10	10	10	5				
Luxembourg ..	1.90	1.81	1.95	2.47	7	8	9	9	0.37	0.44	0.46	0.36	7	8	8	7	11	11	11	8				
Total for 11* countries ..	67.41	80.88	100.27	109.12	1 715	2 243	2 757	2 464	2.55	2.78	2.75	2.44												
World total	80.77	97.72	121.72	133.28																				

the material structure is not uniform, and therefore the strength of the weakest point must be guessed and the steel dimensioned accordingly. An electric steel, on the other hand, has a very uniform structure, and it would therefore seem possible to reduce the factor of safety at least by an amount sufficient to make the total cost of the steel requirements the same whether the steel is manufactured electrically or by one of the other methods. It is undoubtedly along these lines that Germany is working at the present time in order to reduce her internal steel consumption to a minimum.

Of the total quantity of finished steel manufactured in Great Britain, the following is an approximate classification: Miscellaneous sections, 35·8 %; plates, 16·8 %;

of handling 1 000 charges per annum, and the desired output of 2 million tons could be handled by 60 furnaces. Each charge would require a maximum of 9 000 units (kWh), giving an annual consumption per furnace of 9 million units associated with a maximum demand of, say, 3 000 kW. Such a load, on the hypothetical two-part tariff already assumed, would result in an average price of 0·49d. per unit. In actual practice a number of such furnaces would probably be installed in any one works and some benefit would accrue through diversity; this benefit is, however, ignored here.

It may be argued that the assumed plant load-factor is unduly high, seeing that in the U.S.A. in 1936 the aggregate transformer rating for steel furnaces was

Table 16

DIVISION OF OPEN-HEARTH FURNACES ACCORDING TO CAPACITY INSTALLED, 1937

Rating, tons	(A) In Great Britain			(B) In Sheffield only		
	Number	Total capacity	Percentage of total	Number	Total capacity	Percentage of total
Under 20	24	tons 295	1·02	6	tons 75	2·00
20	5	100	0·34	1	20	0·54
25	10	250	0·86	4	100	2·67
30	10	300	1·04	1	30	0·79
35	15	525	1·81	7	245	6·58
40	32	1 280	4·40	6	240	6·43
45	29	1 305	4·47	4	180	4·81
50	59	2 950	10·13	7	350	9·40
55	21	1 155	3·80	4	220	5·89
60	83	4 980	17·11	11	660	17·70
65	13	845	2·91	2	130	3·48
70	11	770	2·65	5	350	9·40
75	29	1 175	7·47	—	—	—
80	21	1 680	5·77	13	1 040	27·91
85	12	1 020	3·51	—	—	—
90	21	1 890	6·49	1	90	2·40
100 and over	47	7 640	26·22	—	—	—
Total	442	29 160	100·00	72	3 730	100·00
50 tons and over	317	25 105	86·06	43	2 840	76·18

sheets, 23·2 %; strip and wire, 14·6 %; rails, 5·3 %; forgings, 3·4 %; springs, 0·9 %. In 1937 the actual tonnage was 9·6 million. If only one-third of the total quantity coming under the headings "sections" and "plates" were manufactured electrically this would be equivalent to 1·7 million tons of finished steel, or, say, 2·7 million tons at the furnace. If, however, factors of safety were reduced to 70 %–80 % of their present value, the actual quantity at the furnace would be 2 million tons per annum.

Assuming a working year of 50 weeks and 132 hours per week with 75 % availability of the furnaces, the actual furnace operating time would be 5 000 hours per annum. Assuming 30- to 35-ton furnaces, with a cycle time of 1 hour tap and recharge and 4 hours refining (5 hours total), each furnace would be capable

532 000 kW (at 0·8 power factor) and the consumption 743 million units, equivalent to a load factor of 16 %. [The comparable figures in the present case are 204 000 kW (3 400 kW per furnace) and 540 million units, or a load factor of 30 %.] It must be recollected, however, that in the present case we are dealing with a refining process only, which, it has already been pointed out, has a better inherent load factor than combined melting and refining such as is required of the American furnaces. Moreover, the furnaces under discussion are intended for a special product, more permanent in character and less liable to severe fluctuations due to national or international conditions. In this connection an American authority* has expressed the opinion that

* Report of Federal Power Commission, 1938, on "Power Requirements in Electrochemical, Electrometallurgical, and Allied Industries."

under the most favourable conditions a 40 % load factor could be reached.

On the basis of the figures assumed above, the approximate cost balance for each furnace would be as shown in Table 17.

If an average selling price of £11 per ton be assumed for this class of steel, the new product will require to be sold at £14.2 per ton. The reduction in total weight due to lower factors of safety would reduce the selling price to £11 again if the reduction were to 77½ % of the present values—a very conservative allowance. Such a reduction in weight would be accompanied by other

Table 17

APPROXIMATE COST BALANCE FOR 30- TO 35-TON FURNACE WITH 1 000 REFINING CHARGES PER ANNUM

Item	Total cost	Cost per ton
	£	£
1 Capital and establishment charges @ 15 % on £60 000	9 000	0.27
2 Labour @ 4 men per shift. £60 per week × 50 weeks	3 000	0.09
3 Slagging materials, repairs, and water, say	25 000	0.75
4 Additions to bath, say	6 500	0.20
5 Electrodes: 160 000 lb. @ 7d. per lb.	4 700	0.14
6 Electricity: 9 million units @ 0.49d. per unit	18 400	0.55
7 Total cost for electric-steel processing	66 600	2.0
8 Equivalent processing cost on finished steel (× 1.6)		3.2

savings, such as on freight to site, lighter foundations, and greater ease of handling generally.

It is suggested, therefore, that the greatest possibility for extending the use of electric steels, apart from the somewhat limited field of special alloy steels, lies in the production of structural sections and plates, where the uniform crystalline formation will show to the greatest advantage

(7) ACKNOWLEDGMENTS

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APPENDIX 1

Determination of the Maximum Power in the Arcs for given Circuit Reactance, Resistance, and Voltage.

The circuit may be regarded as being star-connected, 3-phase (see Fig. 11), each arm having a certain induc-

tance and resistance, and the arc itself being equivalent to an additional resistance.

Let E = phase-to-neutral voltage;
 X = reactance per phase, in ohms;
 r = resistance per phase, in ohms;
 z = impedance due to reactance X and resistance r ;
 R_a = equivalent resistance of arc, in ohms;
 R = total resistance = $r + R_a$;
 Z = total impedance due to reactance X and resistance R ;
 $\cos \theta$ = circuit power-factor;
 I = line current;
 P_r = total power;
 P_a = arc power;
 and $m = P_r/P_a$.

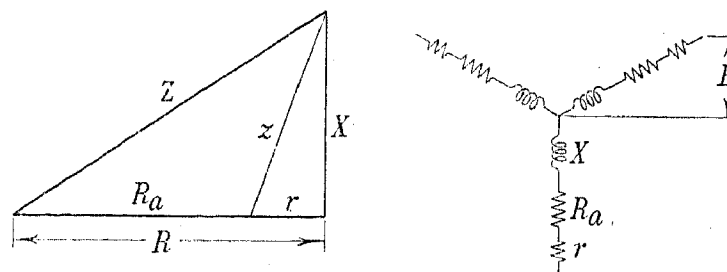


Fig. 11

For a particular furnace the known components are E , X , r , and z . It is required to determine R_a for maximum P_a . We have

$$\begin{aligned}
 P_a &= EI \cos \theta \times \frac{R_a}{R} \\
 &= E \cdot \frac{E}{Z} \times \frac{R}{Z} \times \frac{R_a}{R} \\
 &= \frac{E^2 R_a}{(R_a + r)^2 + X^2} \\
 &= \frac{E^2 R_a}{R_a^2 + 2R_a r + z^2}
 \end{aligned}$$

$$\text{Also } \frac{dP_a}{dR_a} = \frac{(R_a^2 + 2R_a r + z^2)E^2 - E^2 R_a(2R_a + 2r)}{(R_a^2 + 2R_a r + z^2)^2}$$

P_a is a maximum when the above differential is equal to zero, i.e. when

$$R_a = z$$

With maximum arc power we then have

$$P_a = \frac{3E^2 R_a}{R_a^2 + 2R_a r + z^2} = \frac{3E^2}{2000(z + r)} \text{ kilowatts}$$

$$\cos \theta = \frac{R_a + r}{\sqrt{(R_a^2 + 2R_a r + z^2)}} = \sqrt{\left(\frac{z + r}{2z}\right)}$$

$$I = \frac{\sqrt{3}E}{\sqrt{(R_a^2 + 2R_a r + z^2)}} = \sqrt{\left[\frac{3}{2z(z + r)}\right]} E \text{ amperes}$$

$$\text{and } m = \frac{R_a + r}{R_a} = \frac{z + r}{z} \times 100 \text{ as a percentage.}$$

APPENDIX 2

Refractories for lining Electric Furnaces

(Received 3rd April, 1940.)

Arc Furnaces

(1) Acid Process.

It is customary to construct the lining on the bottom of an electric furnace, used for the production of steel by the acid process, with two layers of either fireclay or silica brick covered by a highly refractory rammed ganister or sintered sand. The former type of material would appear to be preferable, and in addition to covering the furnace bottom to a sufficient thickness the ganister is continued in a sloping bank formation up to the slag line.

Side-wall linings vary in thickness from 9 in. up to

So far working results which are available show that an arc-furnace roof built of sillimanite brick has a life more than three times as long as a similar roof built of silica brick, and this additional life more than compensates for the higher initial cost of the sillimanite bricks.

As the doors of an arc furnace are called upon to withstand rapid temperature fluctuations and consequent thermal shocks, it is found necessary to line them either monolithically with high-refractory cement or alternatively with Scotch firebrick.

(2) Basic Process.

The popular class of lining for the furnace bottom is one constructed of magnesite bricks with dolomite

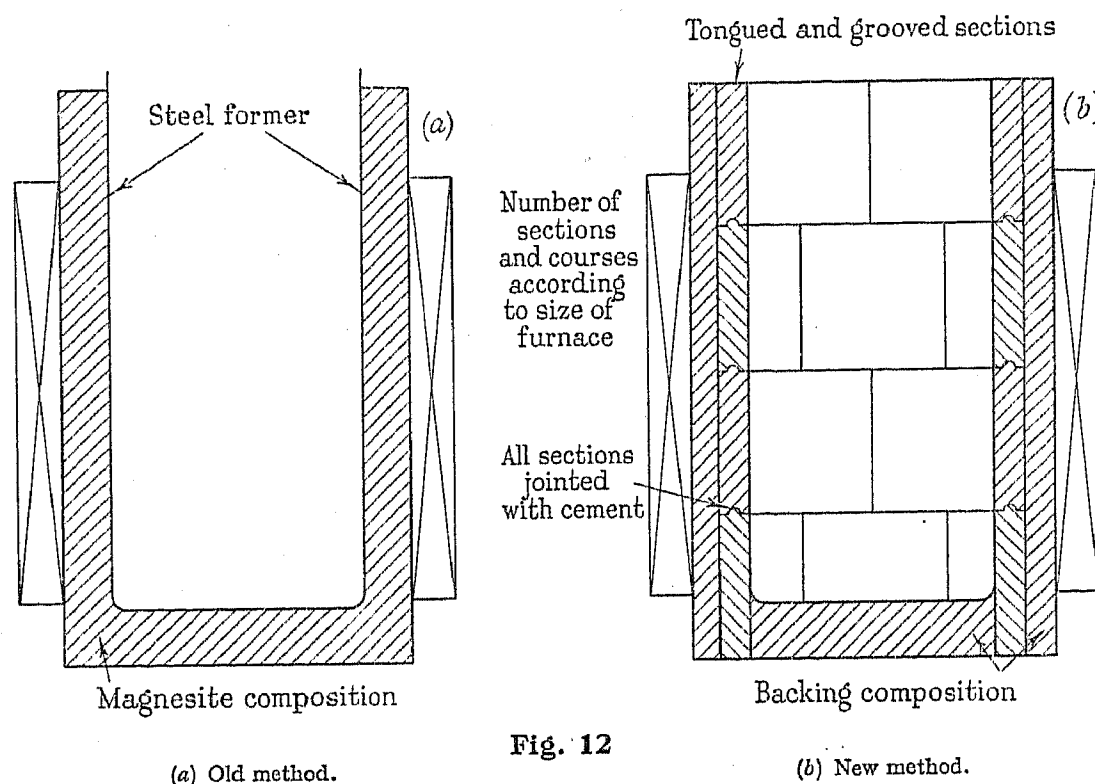


Fig. 12

(a) Old method.

(b) New method.

18 in., according to the capacity of the furnace. Silica crown bricks are invariably used in the side walls, but if the walls require to be particularly thick a composite lining is often employed composed of, say, an inner 9-in. lining of silica bricks with a backing of firebricks or insulating bricks, or sometimes both.

Silica bricks in the past have been regarded as the standard refractory to be used for lining the roof, although it is well known that silica is a nesh refractory and is incapable of withstanding rapid temperature fluctuations. Other refractories sometimes employed in the roof are sillimanite and firebrick. The latter is not to be recommended for large roofs, owing to its erratic expansion and contraction at high temperatures.

Bricks made of sillimanite have come to the fore during the past few years and this material possesses certain properties which would tend to place it in a class by itself for roof construction. For instance, the expansion of bricks made of sillimanite is roughly half that of bricks made of silica and the expansion is perfectly uniform up to a temperature of 1700° C. A good sillimanite brick possesses at least 6 times the spalling resistance of a silica brick, while the former's refractoriness is higher at and near 1700° C.

rammed on top. Once the magnesite bottom has been installed it should have a life of some 6 to 8 years. In view of the high conductivity of magnesite, bricks made of that material require thermal insulation, and it is not unusual to find either a firebrick or high-temperature insulating concrete layer between the magnesite brick and the shell. As a result the molten metal may be separated from the shell, at the bottom of the furnace, by a thickness of 30 in. or more of refractory material and thermal insulation.

Owing to the probable difficulty in obtaining raw magnesite under war conditions, the use of chrome-magnesite bricks in the hearth below the rammed dolomite has been suggested, but where chrome-free steels are being melted they are open to the objection that there is risk of chrome contamination from them. An alternative suggestion is to replace the magnesite bricks by dolomite, but research shows that while dolomite resists molten steel it is not resistant to iron-oxide slags.

In some large-capacity furnaces a skilfully rammed body lining of dolomite is being substituted for the inner brick lining, usually to a depth of 18 in. at the bottom, sloping back to a thickness of 9 in. towards the top of

the furnace sides. Such rammed dolomite body linings are the exception rather than the rule at the moment but, as the technique of installation is mastered, are likely to grow in popularity.

Operating conditions in the basic process are more severe than in the case of the acid process, owing to the long refining period, and, although in other respects the conditions governing the choice of material for the roof construction is similar in the two cases, failure of the roof lining, whether constructed of silica or sillimanite bricks or firebricks, must be expected earlier and more frequently.

The previous remarks concerning refractories used for the doors of acid-process furnaces apply also to the doors of basic-process furnaces.

High-Frequency Induction Furnaces

(1) Acid Process.

The majority of linings of acid-process high-frequency furnaces are constructed on the rammed and fritted principle, with a mixture having as its basis a highly

refractory acid material, behind a former which melts away when the operating temperature of the furnace is reached.

(2) Basic Process.

Where a basic liner is required, basic ramming material is used, on the same principle as for the acid-process high-frequency furnaces.

During the past few years a new and somewhat revolutionary type of basic-process high-frequency furnace lining has appeared on the market, namely one constructed of unfired blocks of basic material prepressed into tongued and grooved sections. For these sections it is preferable to use chrome-magnesite, because this refractory is better able to withstand spalling conditions than ordinary magnesite. Details of this type of construction are shown in Fig. 12.

Numerous linings of this type are now in operation and, as highly successful results are being obtained from furnaces so lined in sizes up to 2 tons capacity, there does not seem to be any reason why furnaces of larger capacity and similarly lined should not prove satisfactory.

WRITTEN CONTRIBUTION TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. W. E. Swale: In the typical installation illustrated in Fig. 2 the instruments are, quite rightly, placed inside a glass-fronted chamber, so that they are protected both from the heat of the furnace and from flying pieces of slag. Yet on page 402 the author suggests the possibility of abolishing the transformer cubicle. The conditions in a steel works are such that it is very desirable to retain the chamber, which can be forced-ventilated by filtered air, so ensuring reasonable operating conditions for sensitive relays and instruments.

With few exceptions electricity supply authorities have given little thought to the implications of these "awkward" loads. The use of arc furnaces is developing rapidly. If units in sizes of 15 to 30 tons are to become common the design of the appropriate high-

voltage networks will certainly require careful attention. The author's clear analysis of the characteristics of arc furnaces is therefore particularly opportune.

The development of the hot-charge process in this country has been disappointing. The arguments in its favour are well summarized in Section (6) of the paper, but when the matter is discussed with manufacturers the objection is usually raised that there is not yet sufficient demand for high-grade structural steels to keep an arc furnace in continuous production. War requirements are giving a great stimulus to electrically-melted alloy steels, and this may well be followed by more rapid development along a wider front.

[The author's reply to this discussion will be found on page 428.]

NORTH MIDLAND CENTRE, AT LEEDS, 18TH NOVEMBER, 1939

Mr. F. S. Naylor: While Fig. 1 illustrates what is probably the largest arc furnace in the country, this design must not be looked upon as representative of the latest practice, for it is provided only with hand charging from side doors and is without the usual feature of a removable top. The present tendency is toward rotating hearths, and while as yet in this country there is little experience of this class of unit it probably represents a step forward, since it tends to spread out the damage to the furnace lining and improves the rate of melting. This feature also is absent from the furnace shown in Fig. 1.

Recently I inspected a furnace in Paris which had an internal diameter of 5.2 m. and a 13 % slope, the rotating feature having limits of ± 30 %.

The author is non-committal on the question of hydraulic control. We ourselves do not favour particularly this class of control, because since the installation is already almost wholly electrical it necessitates the introduction of a different class of fitter and supervision,

thereby adding to running costs. If the equipment is kept wholly electrical, the electrical staff which deals with the rest of the furnace equipment can also handle the electrode control. Furthermore, we have had unfortunate experiences with the effects caused by contact between water and hot steel.

I think there is an error in the author's reference* on page 402 to secondary tapplings. It would be impossible in most cases to arrange such tapplings on an arc-furnace transformer. For example, in an 8 500-kVA transformer which we have recently installed there are six coils per phase in parallel, each coil having 2 turns. It would be impossible to locate 12 tapplings on each secondary 2-turn coil.

The high-frequency induction furnace shown in Fig. 3 is not very representative of present-day practice, which is tending toward conical linings, tapering from 2 in. to 4 in. in a $\frac{1}{2}$ -ton furnace and, say, from 3 in. to 6 in. in a 5-ton furnace. Such a lining is mechanically

* Since altered for the *Journal*.

stronger, and where bottom gouging takes place due to the stirring action in the steel a given lining will last for a longer period by reason of this feature.

On page 404 the author mentions that the number of turns, the coil diameter and the voltage are inter-related, but he does not emphasize the fact that the number of turns is related to the charge which is being melted. It is very necessary in the installation of high-frequency furnaces to ensure that the number of coils is related to the material to be melted. There is a marked difference between the optimum turns for non-magnetic and magnetic steels.

Referring to Fig. 7, the author mentions that the consumption falls to a minimum about 10 minutes after the beginning of the melt, and then rises again. The melting of the steel is due to a combination of hysteresis and eddy-current losses, and from the commencement of the charge up to 700° C. the former is present in a high degree, and therefore the high kilowatt input is possible before this temperature is reached. At 721° C., however, the permeability is reduced to unity, and from then until the charge has been completely melted. While the space factor is poor in the furnace a high kilowatt input is not possible. During this period of the melting, therefore, a dip occurs, as shown in Fig. 7.

On page 406 comparisons are drawn between the units consumption for melting steel in arc furnaces and in high-frequency furnaces; it seems to me that the more important matter is the total units for melting and refining, and I feel that the figures given by the author are misleading since they relate to only part of the cycle.

Quite contrary to the author's findings, for the same operation and for the same size of furnace, steel can be produced at the rate of about 700 units per ton in an arc furnace against 650 units per ton in a high-frequency furnace. There are, however, a very considerable number of factors affecting this issue, so that probably the relative efficiencies are indeterminate.

According to Table 9, an arc furnace produces steel for a fuel-consumption cost of approximately 25s. per ton; a Siemens open-hearth furnace, however, can produce steel for a fuel cost of approximately one-half this figure. It would be interesting to have full details of the relative costs of producing steel from arc furnaces and from Siemens furnaces.

It would seem that the electrical industry must offer a tariff for electricity very nearly equal to the cost of production, if arc furnaces are to be developed to a greater degree, and yet there is no sense in pruning this figure below the economic level. Some electricity supply authorities look upon the arc-furnace load with disfavour, because of the serious fluctuations which can affect the supply to other consumers, but bearing in mind the large revenue possible from these installations it is surely desirable to develop the transmission system in such a way as to avoid the effect of these fluctuations.

In Sheffield the concern with which I am associated had a connected arc-furnace load of approximately 22 000 kVA before the present war, and owing to the necessity of a maximum-demand control, with 33 000-volt feeders to the works, a load of 10 000 kVA was thrown off with little or no effect upon the supply undertaking, so far as other consumers are concerned.

This is largely explained by the fact that the running plant at Blackburn Meadows and Neepsend is normally of the order of at least 150 000 kW. In Sheffield, at any rate, the arc-furnace load is welcomed as a most valuable one.

Provided that supply authorities can remove their prejudices, and provided some accurate figures of relative running costs are forthcoming to enable supply authorities to quote appropriate tariffs, I see no reason why a considerably greater development of this class of load should not be possible.

Mr. W. H. N. James: In the graph shown in Fig. 7 the total power is plotted against time; I should like to know whether the number of turns of the winding in use was constant during the period covered by the graph.

I am inclined to think that an important factor influencing the variation of input is the variation in the permeability of the material in the furnace, which, I think, is ferromagnetic in character. Many years ago I made some tests on the variation of the permeability of iron with temperature, right up to the point at which the permeability became unity. A specimen of meteoric iron was examined in these tests, in order to find out whether such iron had similar properties to ordinary iron. It was found that the permeability rose slowly at first, and then, as red heat was approached, much more rapidly. Finally, when the temperature approached the figure mentioned by the author, the permeability suddenly dropped to unity. In Fig. 7 there is an early drop in power which is very possibly due to the rise in permeability. This is followed by a rather rapid rise in power, which may well be due to a later fall in permeability as the temperature increases.

There is one other point that I should like to raise, also in connection with the high-frequency furnace. There is a statement in the paper to the effect that capacitance correction is very important when alternator-operated furnaces are used, but, on account of the characteristics of the valve circuit, there is not the same need for the use of capacitance correction with valve-operated furnaces. I should be glad if the author would enlarge on the reasons for the difference in practice in the two cases.

Mr. R. M. Longman: The use of a higher-grade steel for building construction where heavy weights and stresses have to be carried would effect a considerable reduction in the weight of the building and the amount of steel required.

It does not appear that electric furnaces have any appreciable effect on the wave form of the supply system.

I am interested in the power factors given in Table 2. In the operating position the power factor is good, and I should like to know the average power factor obtained over a period of normal operation, i.e. obtained from integrating instruments.

The question of keeping electric furnaces off the supply mains at peak-load periods has often been raised; if this idea is adopted it will doubtless lessen the efficiency of electric furnaces. Does the author know of cases in which the idea is being put into practice?

The struggling, untidy arrangement of the heavy electrical connections of many electric furnaces is most

evident, and incidentally is the source of a considerable loss of energy. I should like to know whether any consideration has been given to their reduction or elimination by designing the transformer and furnace as a single unit and providing the flexible connections, if any are required, on the high-voltage side, where the currents are so much smaller.

Finally, I should like to ask the author whether any of the old 2-phase furnaces are still in existence. They used to give a lot of trouble.

Mr. W. Dundas: Reference has been made to the undesirable character of the furnace load from the standpoint of the supply authority, and the violent fluctuations shown on the charts given in the paper may cause other consumers to complain of variations in the voltage unless suitable precautions are taken by the provision of independent feeders. These precautions add to the cost of giving the supply.

I presume that the author's reference in Fig. 5 to a two-part tariff of £3 per kW of maximum demand per annum

and a unit charge of 0.25d. is hypothetical, as it is very doubtful whether a supply authority would obtain the load on that rate.

The figures in Table 6 show considerable variation between the furnace capacity and the kilowatts of maximum demand. For example, in the case of furnace No. 2 the maximum demand is 950 kW, whilst that for furnace No. 17 is 2 500 kW for the same capacity. Again, the melting efficiency per ton does not appear to have any definite relationship with the size of the furnace. It would be of interest to know the reason for these variations.

The load factors of the furnaces, apart from the last four in the Table, which were operated on day shift only, show considerable variations, and in many cases are relatively low; this has an important bearing on the price that can be offered for energy, as exemplified in Fig. 5.

[The author's reply to this discussion will be found on page 428.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 8TH JANUARY, 1940

Mr. W. Scott: I suggest that, to make the paper more complete, the author should include details of the refractories employed in the construction of electric furnaces.

Referring to Table 6, it would be interesting to know why there should be such a wide variation (from 650 to 1 050) in the units per ton of metal melted. The application of electricity to melting should be more of an exact science than these figures indicate.

Finally, I should like to ask what type of steel requires $5\frac{1}{2}$ hours' refining when melted in an electric furnace. We ourselves carry out a fairly wide range of analyses, and I do not think that on any occasion do we exceed a period of 2 hours for refining.

Mr. E. B. Ellis: I consider that the temperature of superheating, which the author gives as 2 000° C., is an extremely high one, and probably much higher than the refractories will stand. In the case of the acid furnace, at this temperature there would be great danger of collapse of the roof or failure of the banks and bottom; and even in the basic-lined furnace, which is normally lined with dolomite and able to withstand considerably higher temperatures, it is usual to construct the roof of a silicious material, and therefore the danger of roof collapse would be present. I should like the author's assurance that this temperature is actually reached, and I should also like to know the nature of the refractories that he would recommend for such service.

Mr. R. W. Mann: It would appear from the discussion that the figures given for load factors will depend on the time period at which the maximum-demand meters have been set. In order that we may consider the author's statements in conjunction with the discussion, perhaps he would indicate the time period of the maximum-demand setting in common use in the area in which the tests have been carried out.

Mr. V. A. H. Clements: The paper seems to divide itself into two parts: first, a description of the metallurgical qualities of electric furnaces and their output; and second, an examination of the costs of fuel (namely

electricity). It is to this latter that I will devote my remarks, particularly as it is to my mind the more important, and since there is general agreement in principle on the former.

According to Table 6, the larger the furnace the worse is the load factor: calculation shows that the average nominal capacity of furnaces Nos. 1-8 is 6.25 tons, and the average load factor about 38 %, whereas for furnaces Nos. 9-16 (leaving out of consideration the "day-shift" furnaces) the figures are 14.375 tons and about 23.4 %. These differences appear inexplicable until it is noted that the time cycle of the latter group is longer, owing to the extra refining, tapping, and recharging time. Thus it follows that the type of output is different, and this leads one to issue a general warning against making any form of generalization when considering the loading characteristics of electric furnaces, a matter which the author appears to have overlooked on more than one occasion. My experience shows that, owing to the effect of several factors, the annual load factor of a single furnace may be anything below 30 % and is very rarely above that figure.

Turning to the section headed "Supply Costs," I am interested that a kW and unit tariff should be one of those that the author gives as an example. Leaving aside any wishes the supply authority may have, I cannot conceive of many electric steel furnace owners agreeing to that form of tariff for an industry which is peculiarly susceptible to trade fluctuations and to a process in which the maximum demand can vary between wide limits, as the author himself shows on page 410. There must, as between the furnace owner and the supply authority, be no misunderstanding as to the probable dangers, as well as the possible benefits, of a tariff embodying an annual demand charge.

Reference to page 410 brings me again to the load-factor question, since here the author discusses "running hours" load factor, which I suggest has nothing to do with the cost of energy; the average prices he thus deduces cannot by any argument be related to fact, and

are thus not only valueless but possibly dangerous to quote.

Regarding the general question of tariffs, I notice that no coal clause is mentioned. This is a most important omission, particularly at the present time, and makes one accept with hesitancy later figures as to cost.

It may be that the references to tariffs, average prices, etc., are hypothetical only, and are not in fact put forward as being practicable. If so, it rather follows that they are valueless for the purposes of those parts of the paper that deal with the economics of the subject.

I think it can be taken as axiomatic that only in exceptional cases is the electric steel-melting load one which, by itself, any undertaking would call profitable. Rather is it necessary for the undertaking to seek ways and means of limiting the lack of profit on so cumbersome a load so that in the general interest it can be dealt with economically from the user's standpoint.

Mr. W. Richardson: In this area we have 8 arc melting furnaces, and this number will be increased in the near future. All these furnaces are in steel foundries making alloy steel castings, as distinct from billets and ingots, and their capacities range from $\frac{1}{2}$ ton to 15 tons.

Turning to Table 6, I think it is a pity that the author does not give some indication of the type of steel made by the furnaces, for it is this which really determines the way in which the furnaces are operated, and consequently their load factor. We find that furnaces used in steel foundries have relatively poor load factors. For example, the highest load factor in this area is 30.8 % with average load factors of 17.5 %. These load factors were obtained during a year of comparatively good trade,

and the figures are much lower when trade conditions are below normal.

On page 409 the author mentions a demand and unit tariff, which he suggests can be applied to electric melting furnaces; I submit that this form of tariff is not suitable for melting furnaces in the foundry industry, in view of the low annual load factors mentioned above.

Turning to the question of the interference which arc furnaces may cause to neighbouring consumers, this question is very important to distributing engineers. The calculation given in Appendix 1 relates to the maximum current which can occur when the bath is molten, and assumes zero resistance in the metal bath. Interference with the voltage of neighbouring consumers is most likely to occur during the melting-down period, owing to the frequent repetition of these short-circuits. The furnace makers tell us that during this period the short-circuits cannot reach their maximum theoretical value, because as the charge is not homogeneous it has an inherent resistance. I wish to ask whether the author has taken or seen any oscillograph records which indicate the relationship between the maximum theoretical current and that actually obtained in practice during the melting-down period. It would be possible to deduce from such records a value for this assumed resistance in the charge.

I wish also to ask whether the author is aware of any developments in refractories which give an indication that at some future date the low-frequency induction furnace may become an economical means of steel-making.

[The author's reply to this discussion will be found on page 428.]

WESTERN CENTRE, AT CARDIFF, 15TH JANUARY, 1940

Mr. W. C. Bowler: When the Transmission Section visited France some few years ago, the French engineers described the method adopted in France for dealing with the load from electric furnaces. Their method, which was governed by the fact that electricity was imported from hydraulic stations outside their own country, was to arrange with the various bulk suppliers that, if they had a surplus quantity of water up in the mountains, the electric furnaces would be kept running for, say, 3 weeks day and night continuously, until such surplus had reached a minimum. Then the works would be closed down, unless a supply of power could be obtained from another source of similar type. It was pointed out by the French engineers that this system worked very well, and of course ensured a very low price per unit.

In all probability this type of load is one which the Central Electricity Board might regard as a summer-time load. If the Board adopted this attitude the furnace load would help them to fill up the valleys in their load curves, thus probably helping the supply undertakers, whose maximum-demand charges would be reduced because of the additional load.

Mr. J. F. Smith: From the steel manufacturer's point of view it is apparent that owing to the substantial quantity of electricity required per ton of product obtained, a quantity which, according to Table 6, varies

from 650 units per ton to 1 050 units per ton, it is necessary in order to produce the product at reasonably competitive prices to obtain electricity at suitably low charges. On the other hand, from the supplier's point of view, the electrical load is not of such a character as to command an attractive rate per unit. Experience with two arc furnaces in South Wales showed that, apart from the stimulus of war conditions, load factors ranged between 15 % and 30 %, and in periods of trade depression could be as low as 6 %. Further, the load was not of an attractive nature, in that it had proved necessary to supply one of the furnaces over quite long transmission lines separate from those dealing with supplies for public and domestic purposes, owing to the heavy voltage fluctuations created by the intermittent nature of the load during the melting period.

Under the heading "Supply Costs" the author mentions a two-part tariff with an alternative flat rate; while it is appreciated that the figures given are for the purpose of illustration only, it is to be assumed that the author as a result of his wide investigation of arc-furnace supplies has adopted charges comparable with those actually in force. It is difficult for supply authorities, unless fortunately placed, to supply arc furnaces at the two-part tariff mentioned by the author or at the flat rate, particularly in the case of isolated furnaces of low load factor. In fact, a comparison between the tariff

mentioned by the author and the Central Electricity Board's published grid tariffs shows that there would be but a very small margin (if any) to cover costs of transmission, local rates, Commissioners' expenses, and such other costs as accrue between the price at the busbars of a power station and that at a consumer's terminals.

The author indicates how the quantity of electrically produced steels in this country could be increased; it appears obvious that the above-mentioned factor, i.e. cost of electricity required, is probably the most important hindrance to greater production of steel by electric furnaces. The problem could be solved by co-operation between the supplier of electricity and the steel maker, since, provided the arc-furnace supply could be restricted to times other than that of peak load on the supply authority's station and main transmission, sufficiently attractive rates could be offered.

In South Wales this restriction has proved practically inoperative, and it is not necessary to specify prolonged periods in each year as "on-peak" periods, since the supply authority's control engineer and the steel manufacturer's engineer can come to an understanding that operation of the furnace will cease on receipt of information from the former that peak-load conditions are anticipated. Power supply engineers will appreciate that it may only be for a few days towards the end of any year that a control engineer will need to stipulate that the furnace shall not be operated, and in fact under some conditions of trading between the C.E.B. and the supply authority such restriction only becomes necessary in certain infrequent years of trading.

Possibly a further solution of the problem would automatically present itself if sufficient furnaces were connected to the supply authority's mains. It has been found from experience in South Wales that heavy intermittent loads such as electric winders and large air compressors, if connected in sufficient numbers to the main power transmission system, tend to produce a resulting load which is quite tolerable even when public service has to be catered for from the same mains. A sufficient number of arc furnaces of moderate size would give the same effect, and the benefit of diversity would make possible a charge per unit more attractive to the steel manufacturer.

The title of the paper appears to be rather inappropriate and possibly a little misleading, as the paper does not deal with (as might be supposed) the properties of electrically manufactured steels but essentially with the electrical production of steel, a very different matter.

Mr. W. A. H. Parker: I should like to comment on this paper purely from the point of view of the supply authority.

I am quite sure that supply authorities will do all they can to encourage the production of high-grade steels in this country. Whilst the steel producer prefers a flat-rate charge per unit, it is highly desirable that the electric-furnace load should develop on sound lines, and if he is able to ignore important points such as load factor, power factor and possible disturbance to other supplies caused by unnecessary variations in load, then the whole problem will become much more difficult from the supply side. I hope that both manufacturers

and users will bear in mind the solution put forward by the author—that of installing several small furnaces instead of one large one for a given output.

Referring to the tariffs mentioned in the paper, unless there are exceptional circumstances I do not think that the user will agree to such figures, but bearing in mind the low load factor of electric furnaces it is difficult to justify much lower prices for energy.

Mr. R. W. Biles: The paper contains much statistical information which deserves a close study. I have found, for instance, from Tables 12, 13 and 14 that between 1935 and 1937 the output of electric steel was practically doubled in this country and Germany, whilst the U.S.A. showed a slightly lower rate of progress.

Table 15 shows that in 1936 Italy had 29.7 % and Sweden 21.48 % of the total steel requirements produced by electricity, while in other countries the percentages were smaller. It would be interesting if the author could throw some light on the cause of the high percentages in these two countries. Are they due to a lack of coal supplies or to the relative cheapness of electricity, due to the presence of water power?

It would be interesting if he could indicate what he considers to be the limiting features at the present time to the greater development of this electrical load.

Mr. S. G. King: With the advent of the grid there has been a tendency to connect arc-furnace equipment to higher supply voltages such as 20 or 33 kV, and this has brought with it a switchgear problem of some magnitude. The trouble is that h.v. switchgear is ordinarily designed for use in power stations and substations where switch service is very infrequent, such as one operation per day or even per week. On the other hand, with arc furnaces the frequency of switch operation may be as much as 50 times per 24-hour day. In addition to this the arc-furnace switches either have to break a heavy current of the order of full-load current, or they have to break the magnetizing current of the arc-furnace transformer. In the latter case the current is at a very low power factor, and for this reason difficulties may arise with some designs of switchgear where the strength of the arc is relied upon to produce a force to extinguish it. Most of these switching operations are necessary because the transformers ordinarily employed with arc furnaces have off-load tap-change apparatus, and it has therefore been suggested that a partial solution to the problem would be to employ on-load tap-change gear. This would have the effect of partly solving one problem and creating another, because present designs of on-load tap-change apparatus are not entirely suitable for very frequent operation. Another difficulty with on-load tap-changing is the very great voltage range necessary with an arc furnace. This range is usually of the order (on a large furnace) of 80–200 volts, a range very much greater than is found in any grid switching station. However, on-load tap-changing has been applied to arc-furnace transformers and we may see more of it in the future, especially on the larger plants.

The author mentions that the upper limit of size of high-frequency furnaces is about 5 tons. I should like to say that this upper limit is determined entirely by considerations of the lining and not by electrical or mechanical difficulties; in fact, in some ways high-

frequency furnace design problems decrease with increase of size. The difficulty with linings is simply that on the larger furnaces the expansion becomes considerable and eventually causes cracking of the lining, with a resultant break-through of molten metal. We are therefore in the hands of the refractory experts, and in fact we are waiting for someone to produce a lining which will have all the necessary characteristics so far as steel melting is concerned, but which will have a low coefficient of expansion. Incidentally, greater trouble is experienced with basic linings than with acid linings so far as cracking is concerned, but unfortunately it is on the larger furnaces that one tends to require a basic lining, and an acid lining will not suffice.

A partial solution of the difficulty is to use a high-frequency generator wound in two separate sections, each feeding one furnace. These furnaces are then poured into the same ladle, so giving twice the quantity of steel normally obtainable.

The author mentions the possibility of there being a considerable diversity factor when a number of arc furnaces are connected to the same supply. This is particularly useful at the present time, when most electricity charges include a maximum-demand figure. It may be of interest to mention here that in the last war in one works there were a number of furnaces connected to the same supply, which was generated locally, and a master regulator was installed in the circuit to limit the total power taken by all the furnaces so as to prevent the generating station from becoming overloaded. The regulator was so arranged that in the event of one furnace

operator calling for more load on his particular furnace, he could obtain a proportion of the extra load as the master regulator automatically reduced the load on all the other furnaces. A new form of master regulator is now being developed to limit the maximum demand, not so much with a view to preventing overloading of generators as in order to keep the maximum-demand charge down to a predetermined and economical figure.

I think it may be interesting to mention a few developments which we may see in the future. One is the use of dual-frequency furnaces, in which a high frequency is used for melting and a low frequency (usually 50 c./s.) is used for stirring the molten charge in order to accelerate the refining action. Progress with this particular type of furnace is really dependent upon the development of a suitable lining. Another possibility which has already been tried is the use of a comparatively standard high-frequency furnace with a roof somewhat similar to an arc-furnace roof and provided with one or more graphite electrodes to superheat the molten charge and refining slag. A variation of this is to make the high-frequency coil of flower-pot shape so as to give a comparatively large bath area, which again accelerates refining. Another scheme which has already been tried out is to build an induction furnace with a hearth shaped somewhat like that of the arc furnace, the coils being pancake-wound and polyphase. This arrangement has the effect of stirring the charge in a peculiar way. The difficulties associated with this scheme are not electrical or mechanical but are connected with the refractory lining.

THE AUTHOR'S REPLY TO THE DISCUSSIONS

Mr. H. A. Sieveking (*in reply*): For convenience the points raised in the discussion can be grouped under four heads, and these will be treated in turn.

(1) Refractories.

In order to cover the points raised under this heading, Appendix 2 dealing with this subject has been added to the paper and no further references will be made here.

(2) Furnace Design.

Mr. Swale appears to think that the abolition of the transformer cubicle of necessity involves the placing of the instruments and control gear in the open as well. This is not the case and it is not suggested that such a procedure should be adopted. As Mr. Longman points out, it is desirable that transformer and furnace should be as close to each other as possible in order to minimize the losses in the leads. It is only occasionally to-day that the straggly connection such as he suggests is seen, and then it is because of site conditions.

Mr. Naylor* is correct in suggesting that the tappings are invariably made on the high-tension side of the transformer. The paper has been amended in this respect. He goes on to the question of rotating hearths and movable roofs for arc furnaces. The former were not considered for the reason he gives, namely that they are

comparatively rare in this country; the latter feature is undoubtedly desirable to-day on furnaces of 20 tons capacity and over, but on smaller sizes the question of the bulkiness of the charge requires consideration and usually, where the bulk/weight ratio is large, the additional expense involved in having a removable roof is not warranted and charging can be as satisfactorily accomplished from the side. His further point with regard to hydraulic versus electric control of the electrodes is a question for the individual user.

There is no doubt that, for high-frequency furnace linings, the form mentioned by Mr. Naylor is preferable, having regard to the wear that occurs at the bottom of the furnace. He is also correct in stating that the number of turns, diameter, and voltage applied to the coil are considerably influenced by the material to be melted.

Mr. King's suggestion that furnace transformers should be fitted with on-load tap-changing is valuable and it is to be hoped that designers will give consideration to this.

(3) Electricity Consumptions and Power Costs.

A number of speakers have criticized the two-part tariff put forward on the grounds that it would be unacceptable to a furnace user. Others have suggested that it is the only fair means of charging, and one has gone so far as to suggest that the tariff mentioned in the paper is too low for a supply undertaking purchasing current at the grid tariff. First of all I should like to emphasize

* In connection with these remarks, and also my reply to Mr. King in the next column, see *Electrical Service*, 1939-40, Nos. 11-12, pp. 205-210.

that both the two-part and the flat-rate tariffs put forward are purely hypothetical, and in practice it would also be essential to include a coal clause. The suggestion that the two-part type of tariff is unacceptable is not borne out in practice, as there are a large number of cases where it is used. Whether the one quoted in the paper is economic or otherwise must of necessity depend upon local conditions, both as regards the manufacturer and the supply undertaking, but where no special transmission charges have to be met or where they are paid for by the user, the tariff suggested (with a coal clause) would be reasonable for a supply undertaking purchasing current at the grid tariff if the undertaking is of any magnitude.

A number of speakers have also commented on the question of load factors, Mr. Clements in particular suggesting that to mention running-hour load factor, not annual load factor, is misleading. It is agreed that, in the great majority of cases, arc-furnace load factors will lie well below 30 % for individual units. The extent to which they fall below this figure will depend mainly on the production programme of the works in which the furnace is installed, and to introduce the completely unknown factor of degree of operation when discussing the effect of control of the electrodes on the maximum demand would, it is suggested, be more misleading than to consider merely running-hour load factor, which only requires to be multiplied by a certain factor in order to obtain the annual load factor.

Throughout the paper the maximum demand referred to is that obtained from a half-hour period of integration.

In general terms, in addition to the factors mentioned above, the load factor is a function of the initial charge as well as the degree of accuracy required in the ultimate analysis. In other words, it is dependent to a very large extent on the refining period and consumption as pointed out in the paper.

I agree with Mr. Naylor that it is very desirable that comparative total costs of production using open-hearth and electric furnaces should be made available.

Mr. Longman and Mr. Bowler suggest that consideration should be given to off-peak operation. This is by no means a novel suggestion and many efforts have been directed towards achieving this. It is not quite clear what Mr. Bowler means by his suggestion that the Central Electricity Board might consider the load a "summer one," as if it occurred during the summer months it naturally would be summer load, and subject to certain limitations no additional maximum demand charge would be payable by the supply undertaking. Such a load would not, however, as suggested, reduce the maximum demand charge already payable.

Mr. Smith's suggestion that the electric furnace should be considered as an off-peak load and the on-peak period controlled by telephone is an admirable one, when such close co-operation between the steel manufacturer and the supply undertaking can be achieved.

Mr. Dundas draws attention to the supply undertakings' difficulties in meeting possible voltage fluctuations due to an arc furnace or furnaces being connected to their mains. The degree of fluctuation will depend on the proportion of furnace load to the load on the feeder, and it is only when this proportion is high that disturbances to other consumers will arise.

Mr. Clements makes what is, in my opinion, a dangerous suggestion, namely that the electric furnace load must be accepted at an uneconomic price and the deficit made up in other ways. A carefully chosen tariff for the whole of a works will enable the same total revenue to be obtained, and it is then purely a question of works accounting as to the proportion that should be borne by the furnace and by the remainder of the works respectively.

Mr. Naylor suggests that for a true comparison to be made between the electricity consumptions of high-frequency and arc furnaces the total consumption in both cases should be taken. I am unable to agree with this view for two reasons:—

(a) The high-frequency furnace is not used for refining, and

(b) The electricity consumption for refining with an arc furnace varies widely.

A true comparison, therefore, can only be made on the number of units used for melting purposes alone, as has been done in the paper.

Mr. Dundas refers to transformer sizes. Broadly, the sizes quoted in Table 2 are those that would be met at the present day. Departures from the quoted figures may occur for a number of reasons. For example, when the furnace is used for melting only the size may be increased without affecting the load factor, as an increase in transformer size would enable a quicker melt to be obtained. Again, under war conditions, where a rapid output is needed, similar arguments may apply, even when there is a refining period following the melting, as the influence of the maximum-demand charge, where a two-part tariff is used, is of less moment than under peace conditions. Some of the furnaces mentioned in the Tables in the paper were installed over 20 years ago, and the transformer sizes are frequently below what would be considered desirable under present-day conditions.

Mr. Scott comments on the wide variation in melting consumptions. This is due to a number of causes, for example general furnace design, that is to say whether the furnace is old or of modern type; the skill of the operator; the size of the transformer (influencing the melting period); and the material of the charge. Long refining periods are occasionally required when the initial charges are of a very poor quality and a particularly accurate analysis is required for the final output. Also, if the initial charge has chromium present and this is required in the final output some time may be taken up in recovering the chromium from the slag.

(4) General.

Mr. Smith criticized the title of the paper on the ground that it is misleading and inappropriate. If the intention had been to discuss the properties of steel, the word "property" would have been introduced into the title. Again the word "production" implies, to-day, a finished article rather than an intermediate stage in its manufacture, and would therefore have been even more inappropriate.

Mr. Naylor's comment regarding the throwing on or off of 10 000 kVA of load in the Sheffield district is of interest,

but I suggest that the reason why it has so little effect is rather the linking up of the Sheffield Corporation's generating station with the national system. Mr. James refers more particularly to the high-frequency furnace. The number of turns of the coil used when obtaining the graph shown in Fig. 7 was constant and it is of considerable interest that Mr. James's experiments go to prove the suggestion made in the paper as to why there is a dip in the load curve.

With regard to the question of condensers in the circuit, Mr. James has been slightly misled. There is a variable (tuning) condenser in the valve circuit, but owing to the

very high frequency employed it is relatively small compared with those used with alternator-operated furnaces, and for that reason does not need the elaborate contactor gear that is needed to operate the latter type.

Mr. Richardson suggests that in practice a figure of less than twice normal full-load current can be taken when designing mains for arc-furnace loads. Generally speaking, it is unnecessary to assume the figure above quoted, and in practice the instantaneous current fluctuations rarely exceed $1\frac{1}{2}$ times full-load current, "full load" in this case being taken to mean the load at the maximum arc power position.

DISCUSSION ON

"DEFORMATION OF TURBO-ALTERNATOR ROTOR WINDINGS, DUE TO TEMPERATURE RISE"*

Mr. W. D. Horsley (*communicated*): A general explanation of rotor-coil distortion has been understood for some time, but as far as can be ascertained the author is the first to give a detailed analysis of the problem. His treatment shows that the temperature rise of the windings is a very critical factor.

As stated in the paper the calculations are based upon a number of assumptions, and it should be made clear that the actual limiting temperature above which coil distortion may occur may vary considerably from the value given by the curves in Fig. 6. These curves show that if any of the turns in the rotor winding have a temperature rise exceeding 95 deg. C. above the initial temperature of the rotor they are liable to shrinkage.

The temperature rise of the copper is not uniform throughout the winding and, in addition to the top turns in the slot being cooler than those near the bottom, the coils adjacent to the pole are cooler than the outer coils. Under these conditions, if the maximum temperature rise is limited to 95 deg. C., the average temperature rise of the embedded portion of the winding cannot exceed 70 to 75 deg. C. If the end windings of the rotor are cooler than the embedded portion the average value must be even lower.

The calculations to determine the limiting temperature rise are based on the stress/strain curve given in Fig. 2, which appears to be characteristic of a copper having a Brinell hardness value of 70 to 75. A softer copper having a hardness of 50 to 55 has commonly been used for rotor windings and the limiting temperature rise at which coil shrinkage occurs is therefore less than 95 deg. C., and the average temperature rise would be correspondingly lowered. A further reduction is necessary if the air inlet-temperature to the alternator becomes greater than the initial temperature of the rotor.

Taking all these factors into consideration it would appear to be necessary, in order to avoid coil distortion,

to design the alternator with a temperature rise of the rotor winding not exceeding 50 deg. C. by resistance above the air inlet-temperature. On the other hand, it is known that many rotors are operating at much higher temperature limits and under adverse conditions of operation without showing any signs of coil distortion.

It is clear that other factors are involved and, while a reduction in temperature rise would be an advantage, the limiting value below which coil distortion could not occur is uneconomical and impracticable for large plant.

The use of hard-drawn copper is a possible solution, but, as the author points out, gradual annealing of the copper takes place at a comparatively low temperature.

The most satisfactory solution appears to be to support the rotor coils against contraction by suitably designed packings.

Mr. P. Richardson (*communicated*): The paper provides a simple explanation of the phenomenon of rotor-coil deformation, and the neat method of determining the amount of contraction of copper for various copper and iron temperatures shows the effect of temperature. The methods of obviating the trouble, however, are of more interest to the engineer in charge of turbo plant, and it is in this part of the paper that I am interested. The possibility of pre-heating the rotor at a low speed is a reasonable solution of the difficulty, and may be employed where a rotor has not had special packing inserted in the end windings. At the same time it introduces the necessity of an auxiliary d.c. supply, and care must be exercised regarding the temperature to which the windings should be heated; difficulties may arise owing to excessive heating of the rotor end-windings at a low speed on account of poor air circulation. These difficulties are aggravated where the set is run up daily or is required at short notice. The method which seemingly offers the best solution is to prevent the rotor coil-ends from moving.

Fig. 9, showing that the maximum tensile stress is

* Paper by Mr. G. A. JUHLIN (see *Journal I.E.E.*, 85, p. 544).

limited to a safe value, does not appear to be correct. Firstly, am I correct in assuming that there is a misprint where the text states "When the rotor cools the stress falls along line $A_1 A_2$ until at a point A_2 it intersects a line OX_2 drawn from O at right angles to OA_1 "? From the diagram it appears that the line OA_1 should be the line OA.

It is a peculiar feature of this construction that re-drawing the diagram in Fig. 9 to a different horizontal scale, i.e. altering the inclination of the slopes, results in different values of resultant tensile stress. For example, if the horizontal scale is halved and the construction described in the paper carefully followed it is found that the final tensile stress of 4 350 lb. per sq. in. is reduced to less than 3 500 lb. per sq. in. The construction appears to be at fault.

It would appear more reasonable to determine the maximum resultant tensile stress likely to be experienced, by producing the line $A_1 A_2$ until it intersects the vertical stress ordinate. It is an essential of this construction that the ends of the rotor coils are assumed fixed; consequently, the strain giving rise to tensile stress in the copper is proportional to the product of the permanent set per unit length and the length of the copper undergoing contraction. The stress may thus be obtained direct from the stress/strain curve. Where the length of copper undergoing contraction is large compared with the total length of the coil, the resultant tensile stress is given on the diagram by the intercept of the line $A_1 A_2$ with the vertical ordinate. The maximum tensile stress would therefore be about 7 000 lb. per sq. in. This presents another difficulty. The author gives in Fig. 2 a stress/strain curve for the copper employed in the rotor winding, and it appears to be drawn for a partially work-hardened copper. Presumably, as mentioned later in the paper, the ends of the rotor coils are annealed to facilitate manufacture, and in this case the stress/strain curve of the annealed copper would be considerably lower than that shown, having an elastic limit of about 3 000 lb. per sq. in. The tensile stress obtainable is greatly in excess of the elastic limit of annealed copper, and it would appear that the disadvantage of rigidly supporting the ends of the coils is that the copper contraction in the rotor slot may cause stretching of the copper in the end winding. Admittedly the end-winding copper may work-harden, thereby raising its elastic limit above the maximum value of stress obtainable, but the end windings may suffer permanent damage.

Mr. G. A. Juhlin (*in reply*): I think Mr. Horsley is under some misapprehension, as it is clear from Fig. 6 that distortion takes place at temperature rises lower than 95 deg. C. The curves in Fig. 6 show clearly that the amount of contraction increases very rapidly with increasing temperature rise, which fact I have endeavoured to emphasize in the paper.

It is quite correct that the temperature of the copper is not uniform throughout the winding, but this fact has no bearing on the problem dealt with.

It is clearly stated in the paper that the end windings

are left out of consideration, and for this reason the temperature rise refers to the slot portion of the winding. It has been made clear in Fig. 7 that only a part towards the centre of the rotor is prevented from expanding, and the temperature rise must therefore refer to this portion of the winding and not to the average temperature rise of the whole winding. It is, of course, recognized that this average temperature rise is lower than the maximum temperature rise in the slot portion, but no attempt has been made in the paper to correlate these temperature rises.

The stress/strain curve shown in Fig. 2 was taken from the actual machine and some hardening may have taken place during operation, although it was taken from the slot near the end of the rotor. I do not think the assumption that it would be necessary to design rotors for a temperature rise of 50 deg. C. by resistance in order to avoid distortion is justified. The fact that, as Mr. Horsley points out, many rotors are known to operate at much higher temperatures without troubles shows that the temperature rise by resistance is much nearer to the maximum than Mr. Horsley assumes. I do not think it is safe to assume that because no troubles have been experienced no distortion has taken place, as I believe that many rotors would be found where distortion has taken place but not of sufficient magnitude to cause any troubles.

Mr. Richardson is, of course, correct in pointing out that the best solution for overcoming deformation is to support the copper against axial deformation.

Referring to Fig. 9, I am glad to have had what is clearly an error pointed out. This has arisen owing to the desire to simplify the drawing of the diagram by assuming that lines OX_2 and AX_1 would be at right angles to OA. The correct procedure in drawing the diagram is as follows:—

When the rotor cools after the first run the stress falls along the line $A_1 A_2$ and the strain which remains is obtained from the intersection of the line $A_1 A_2$ with the zero line at I. From this strain we can calculate the negative stress required for balance. The ordinate of A_2 is equal to this stress, and the line OX_2 is drawn through this point. Line AX_1 is drawn parallel to OX_2 and is not necessarily at right angles to OA.

With regard to the stress/strain curve, I have dealt with this already. It was pointed out in the paper that it is not possible to fix the ends of the coils absolutely rigidly, and the case was given as a matter of interest.

Mr. Richardson sets out with the opinion that "the method which seemingly offers the best solution is to prevent the rotor coil-ends from moving." Later he states "it would appear that the disadvantage of rigidly supporting the ends of the coils is that the copper contraction in the rotor slot may cause stretching of the copper in the end winding."

It is not possible to support the end windings sufficiently to prevent all movements and this is not necessary, but in any case stresses will be present and must be kept sufficiently low not to cause dangerous deformation.

THE DESIGN OF A LOUD-SPEAKER

By W WEST, B.A., Member,* and D. McMILLAN, B.Sc., Associate Member.*

(Paper first received 3rd May, and in revised form 31st October, 1939. The paper would have been read and discussed before the WIRELESS SECTION on the 6th December, 1939, but the meeting was cancelled owing to the war.)

SUMMARY

This paper gives an account of an investigation of the requirements for design of a loud-speaker for use in living-rooms. The design which resulted from the investigation is described, and there is also some discussion of the criteria of quality of performance which have been adopted.

Essential requirements were that the loud-speaker should be capable of standardization to a design which would be inexpensive for production in quantity; and that the quality of reproduction should be superior to that generally supplied by available commercial instruments—in fact, that the loud-speaker should be as near to perfection as is economically possible. The question of size was discussed during the investigation when some knowledge of the limitations thereby imposed on the quality of reproduction had been gained, and a compromise was struck between conflicting requirements.

The investigation was carried to the point where a specification was issued to interested contractors, and tenders for the manufacture of loud-speakers were invited. Under the terms of this specification, samples were submitted by several contractors, and some of the samples submitted were satisfactory both as to performance and as to price. The development of the design, though fairly complete, does not include experience with the mass-produced article, or with methods of acceptance testing of supplies in bulk.

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(1) CRITERIA OF PERFORMANCE

As a preliminary to the design of a loud-speaker, it was considered essential to attempt to formulate a subjective and an objective criterion of performance.

(1.1) Subjective Criterion

The subjective criterion should represent the ideal of performance at which the design should aim. This is a somewhat arbitrary and controversial point. Since the loud-speakers may be used for programme transmissions to be heard in domestic living-rooms, the criterion which has been adopted for this design is one of faithfulness of reproduction of individual sources of sound in a typical living-room, by comparison with the identical original sources heard in the same room. This criterion rules out of direct consideration such sources as large orchestras, bands, etc., which are not listened to, as original sources of sound, in such a room. Nevertheless, it is thought that it is at least as relevant as any other possible criterion to the reception of such classes of programme.

A fairly rapid and direct comparison between the reproduced and the original sound can be made by fitting two rooms, close together, as studio and typical living room respectively, and transferring the source of sound alternately between the two, listening only in the living room. Alternatively, the listener can go from one room to the other, the source remaining in the studio, but this method is not preferred, as the ear must adapt itself, in the comparison, to the different acoustics of the two rooms. In either case the acoustics of both rooms influence the reproduced sound, but one room only is concerned in the direct sound. With complete control of the whole transmission system, the studio can be made relatively dead, so that its influence on the reproduced sound is relatively slight. It was under such conditions and with a studio about twice as large as the listening room that tests of judgment of fidelity were made and a very high degree of fidelity was found to be possible [see Section (4.5), last paragraph]. When the loud-speaker is used for programmes from a studio of the B.B.C., the influence of the acoustics of the studio must

enter to the extent permitted by the technique employed for studio design and use.

The sources of sound readily available for fidelity judgments include the speaking and singing voice, readily portable musical instruments, and a variety of common sounds, such as the rustling of paper. Some practice is, of course, necessary to ensure that the volumes of the transmitted and the direct sounds are well balanced.

During the course of the investigation some judgment tests of this kind were made from time to time, chiefly to reach decisions as to what loss of quality, from the best which had been attained, might be tolerated to effect necessary reductions in size and cost of the loud-speaker.

(1.2) Objective Criterion

These subjective tests are tedious and often somewhat inconclusive, and it is obvious that a simple objective criterion is required for the very great quantity of testing of details which is required to design a loud-speaker.

Previous experience with conventional constructions of loud-speakers has indicated that frequency distortion has the predominant influence on quality, and that other kinds of distortion would not be noticed, at least until a very high degree of perfection is reached in the elimination of frequency distortion by the loud-speaker, and of all distortions in the rest of the transmitting or reproducing system. For the objective criterion a frequency-characteristic test is therefore indicated.

Apparatus was available for recording the frequency characteristic of a loud-speaker in acoustic conditions equivalent to free space, in terms of the sound pressure at a point when the loud-speaker was energized by a constant p.d., at variable frequency, applied to the input of a power amplifier, in the design of which special precautions had been taken to avoid all forms of distortion. The condenser microphone for measuring the sound pressures was used in conjunction with an amplifier having a compensating frequency characteristic, and the sound pressures were recorded on a linear scale. The acoustically dead testing-room was proved to exert no appreciable influence on frequency characteristics taken at 2 ft. distance from a loud-speaker, by repeating at different positions in the room tests of a loud-speaker and microphone always in the same relative position with respect to each other. With a spacing distance of 2 ft. practically identical frequency-characteristics were obtained, but substantial divergences at certain frequencies were found when the distance was increased to 4 ft.

Because of the unequal polar distribution characteristics of loud-speakers it is not, in general, sufficient to judge the performance of a loud-speaker in terms of a frequency characteristic taken at a single point in free space. For a simple objective criterion it was, however, most desirable to make use of a single curve which can be recorded in 1 or 2 minutes, e.g. that of the sound pressure in free space at a point on the axis 2 ft. in front of the open face of the loud-speaker.

With this end in view a series of experiments was undertaken [see Section (2)] to compare the axial

response, firstly with the mean spherical response (both in free-space conditions), and then with the characteristic of the average sound pressure generated in one or two different rooms of the "typical living-room" class.

For loud-speakers which are effectively enclosed behind the diaphragm and which have the same size of diaphragm, and approximately the same size of cabinet, the relation between the axial and the mean-spherical responses may be regarded practically as a fixed quantity. This relation, when established, can be used to convert the axial response curve into the mean-spherical response curve. If the casing of the loud-speaker is open or partly open at the back, different relations will apply.

For reasons given hereafter it was decided to design the loud-speaker with an enclosing case, and the relation, obtained as described in Section (2.3), between the axial response and the mean spherical response was used. The subjective judgment tests substantially confirmed the hypothesis that, for relating the performance as measured under free-space conditions with that measured under ordinary conditions of use, the mean spherical response is the most applicable; a simple objective criterion was thus established. Briefly stated, this criterion is that the axial frequency-characteristic should approximate as closely as possible to a curve rising smoothly, as the frequency is increased, at a rate of 2.5 db. per octave.

Finally, it was thought to be necessary to formulate a working policy regarding the range of frequencies which the loud-speaker should effectively handle, since it was clear that limitations would be imposed by practical considerations. The policy adopted, stated in general terms, was as follows: The mean spherical response in free space should be as uniform as possible throughout the range of frequencies from 100 to 4 000 c./s.; beyond these limits powerful resonances should be avoided and the uniformity of response should be maintained as far as possible, but no substantial sacrifice of the response within this range should be permitted for the sake of improving the response outside the range.

(2) COMPARISON OF FREQUENCY CHARACTERISTICS OF A LOUD-SPEAKER TAKEN BY VARIOUS METHODS, BOTH IN FREE SPACE AND IN TYPICAL LIVING-ROOMS

The procedure of the tests was generally as follows:—
(a) A sample loud-speaker was selected for study in detail. (b) A series of frequency characteristics of this loud-speaker was measured for different directions of radiation in free space. (c) The mean spherical sound pressure was calculated from these curves, and the relation between the frequency characteristics of mean-spherical sound pressures and of axial sound pressures was noted. (d) The frequency characteristic of the average sound pressure in a typical room was measured (by a method to be described later) and compared with the curves obtained from (c). (e) Transmission by the loud-speaker was compared aurally with the original source on a high-quality system.

Part or all of this test procedure was followed for various loud-speakers.

(2.1) Measurement of Axial and Mean-Spherical Characteristics in Free-Space Conditions

The term "mean spherical sound pressure at a certain distance from the loud-speaker in free space" is here used to refer to the sound pressure which would have existed at the same point if the loud-speaker had been emitting the same total power by spherical radiation.

The measurements of sound pressure were carried out in the acoustically dead testing-room at a distance of 2 ft. from the loud-speaker and at positions subtending angles of 0, 30°, 60°, 90°, 120°, 150°, and 180° with the axis at the centre of the diaphragm. The measurements at zero angle give the axial sound pressure.

The mean spherical sound pressure P was calculated from the measurements at the various positions by means of the formula

$$P = \sqrt{[0.015(P_0^2 + P_{180}^2) + 0.13(P_{30}^2 + P_{150}^2) + 0.225(P_{60}^2 + P_{120}^2) + 0.26P_{90}^2]}$$

wherein P_0 , P_{30} , P_{60} , etc., represent the sound pressures measured at the angles 0, 30°, 60°, etc. This formula is based on considerations of power radiated into concentric divisions of space, and is an extension of a formula used elsewhere.*

(2.2) Measurement of Average Sound-Pressure Characteristics in a Typical Room

These measurements were made in rooms having acoustical characteristics adjusted so that they were judged to be similar to those commonly found in the rooms of dwelling houses. A "warble tone" was used, a frequency modulation of about ± 20 c./s. being applied to the output of the oscillator supplying the testing tone. The complete cycle of frequency modulation occurred about 5 times per second. The loud-speaker to be tested was set up in a suitable position in the room and fed with current from the warble-tone oscillator. Measurements of sound pressure were made at various points in the room using a small, and substantially non-directional, condenser transmitter in association with a rectifier voltmeter having characteristics which conformed to those recommended in the American Tentative Standards.† This voltmeter was calibrated in decibels relative to an arbitrary level of p.d., and hence the combination of calibrated microphone, amplifier, and voltmeter could readily be calibrated in decibels relative to an arbitrary level of sound pressure.

Some preliminary experiments were made to decide upon a suitable technique of testing to obtain a measure of the average sound pressure in the room. No satisfactory alternative was found to the lengthy process of statistical survey, involving a large number of individual measurements at each frequency tested. The measurements were grouped into batches of nine, taken at the eight corners and centre of a cube of space with sides of 4 ft. A wire frame of this shape was suspended in the room to locate the positions for each group of measurements.

Statistical analysis was applied to many test results, and it was found that if the measurements were expressed in dynes per cm² the distribution of individual readings did not follow the normal error law. If, however, they were expressed in decibels (relative to an arbitrarily fixed value), the distribution did obey, very closely, the normal error law. This result was verified by five separate test-conditions involving different frequencies and different positions of loud-speaker and testing points within the room.

It follows that the arithmetic average of the measurements, expressed in decibels, gives the most probable value (in the statistical sense) of the sound pressure. This method of averaging has therefore been used for all the measurements of average sound pressure in typical rooms which are quoted below.

It is of interest to record that, in a typical series of 48 readings, the standard deviation of the individual readings was 3.2 db. Also it was found that any one frequency characteristic, obtained from groups of nine observations only per frequency, might differ from a characteristic obtained from a much larger number of observations by as much as 10 db. at individual frequencies. A reasonably stable mean curve was obtained from 54 observations (e.g. three different positions of the locating frame for each of two positions of loud-speaker), and such a curve was repeatable within about 2 db. at any individual frequency. In the test results quoted below, each test point is an average of at least 54 individual readings.

(2.3) Results of Tests

The frequency characteristics of axial sound pressure and mean spherical sound pressure in free space, and average sound in a typical room, have been measured for a number of different loud-speakers. The results, obtained on two samples having completely enclosing cases are described in this Section.

Loud-speaker A.—This instrument was an experimental model moving-coil loud-speaker having a paper cone of 7 in. diameter and a totally enclosed, heavily soundproofed case with an internal volume of about 8 500 cm³. The case of this loud-speaker was cylindrical in form and therefore symmetrical about the axis of the moving coil. The main resonance of the suspension was heavily damped by sound-absorbing material situated within the case and fairly close behind the diaphragm.

Various frequency-characteristic curves obtained with this loud-speaker are illustrated in Fig. 1. Curve 1 shows the shape of the frequency characteristic of axial sound pressure, and Curve 2 shows the mean spherical sound pressure [both in free space, see Section (2.1)]. It will be seen that the curve of mean spherical sound pressure shows a reasonably constant sensitivity over the range 300 to 4 000 c./s. Outside this range the sensitivity drops rapidly. This characteristic may be said to confirm the impressions obtained from the fidelity judgment tests. The limitation at low frequencies is reasonable in view of the large acoustical stiffness introduced by the comparatively small volume of air enclosed behind the diaphragm of the loud-speaker. On the other hand, the axial sound-pressure curve indicates a rising sensitivity over the range 300 to 4 000

* "American Tentative Standards for Sound Level Meters," *Journal of the Acoustical Society of America*, 1936, vol. 8, p. 147, Appendix 1.

† *Loc. cit.*

c./s. From these two curves it is a simple matter to draw a third curve showing the ideal axial response to result in a constant mean-spherical sound-pressure sensitivity for a loud-speaker of the particular type under discussion.

The points marked by crosses in Fig. 2, obtained from the differences between the ordinates of Curves 1 and 2 of Fig. 1, approximate to the straight line which has a

sure indicates a good response down to 100 c./s., which is certainly not correct for the loud-speaker under consideration. This apparent increase in low-frequency sensitivity, as measured by the warble-tone test in this room, is therefore to be regarded as a function of the room rather than of the loud-speaker.

Fig. 3 shows two frequency characteristics of average sound pressure for Loud-speaker A. Curve 1 is a repro-

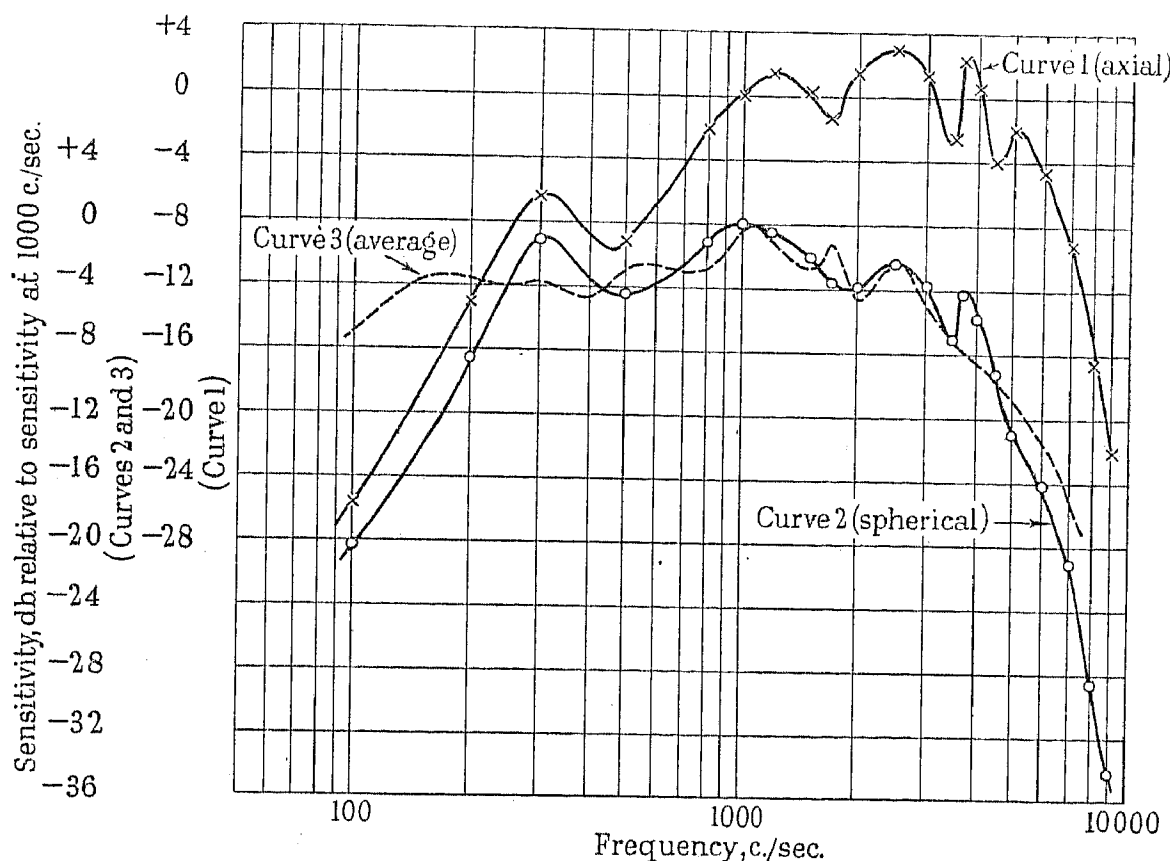


Fig. 1.—Comparison of sound pressures, axial and mean spherical (in free space) and average (in typical room), for Loud-speaker A.

slope of 2.5 db. per octave, and which can be regarded as the required shape for the axial response of this loud-speaker to give uniform total power radiated in free space.

Curve 3 of Fig. 1 shows the shape of the frequency characteristic of average sound pressure [Section (2.2)] in the room used for listening when making fidelity judgment tests. This room had approximate dimensions 24 ft. $\times$ 12 ft. $\times$ 11 ft. 6 in. high and included sound-absorbing material on the ceiling, a carpet on the floor, and some additional sound-absorbing material hung on the walls to produce an acoustical environment similar to that found in a well-furnished living-room. (This room will be called Room X.) It will be seen that the frequency response of average sound pressure in Room X agrees fairly closely with the curve of mean spherical sound pressure in free space (Curve 2) for all frequencies above 250 c./s. Room X was the room in which the fidelity judgments had been made, so that it may be said that, for frequencies above 250 c./s., both the curve of mean spherical sound pressure in free space and the curve of average sound pressure in a typical room confirm the subjective impression obtained from the fidelity test. Below 250 c./s. the curve of mean spherical sound pressure more nearly illustrates the subjective effect. The curve of average sound pres-

duction of Curve 3 of Fig. 1, and Curve 2 illustrates the results of a series of warble-tone tests made in a different room (Room Y). This room had somewhat larger

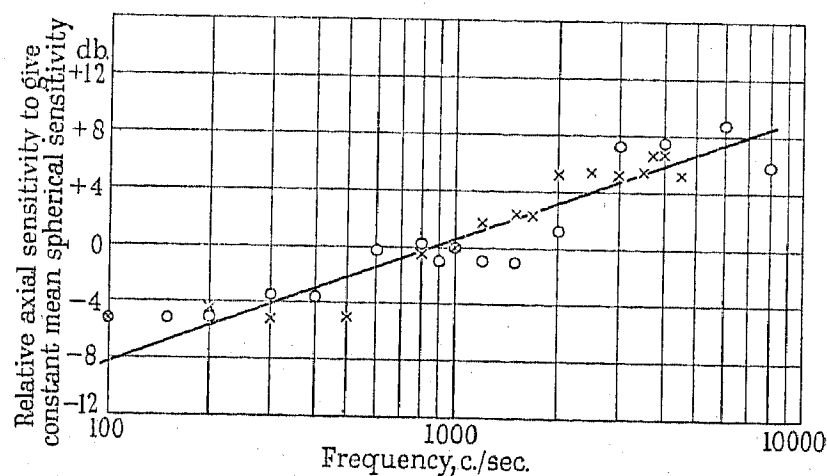


Fig. 2.—Relative axial sensitivity for constant mean spherical sensitivity.

X Loud-speaker A. O Loud-speaker B.

dimensions than Room X, being 28 ft. $\times$ 14 ft. $\times$ 11 ft. 6 in. high, and included less sound-absorbing materials. In particular, the walls of this room were hard and smooth, so that the absorption of the higher frequencies,

which are radiated in a comparatively narrow beam from the loud-speaker, was probably relatively small. It will be seen that the curves for the two rooms agree reasonably well over the frequency range 100 to 3 000 c./s. Above this latter frequency the response in Room Y is

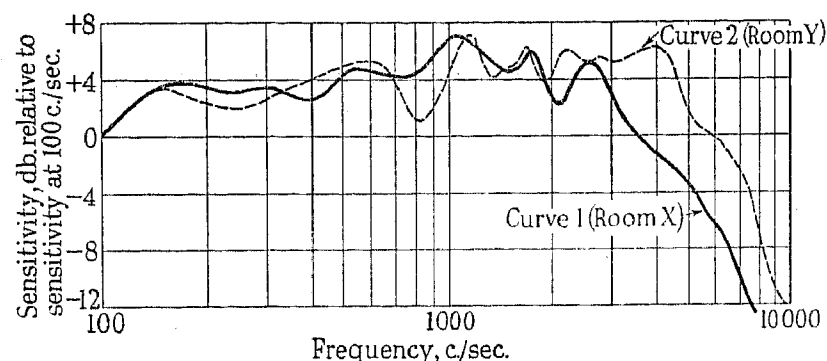


Fig. 3.—Average sound pressures in two rooms: Loud-speaker A.

greater than that obtained in Room X. Presumably the difference in the absorption-frequency characteristics of the two rooms accounts for this effect.

Loud-speaker B.—This instrument was constructed in accordance with the specification given in Section (5).

Fig. 4 illustrates three curves of frequency response for this loud-speaker. Curve 1 shows the axial sound

Curve 3 of Fig. 4 shows the frequency characteristic of average sound pressures for this loud-speaker, taken in Room X. It will be seen that the points fall closely about the curve of mean spherical sound pressure for all frequencies above 600 c./s. Below this frequency there is some divergence, and again the curve of average sound pressures indicates an unexpectedly large output from the loud-speaker for very low frequencies (below 200 c./s.). This effect is most probably to be attributed to the room rather than to the loud-speaker.

(2.4) Comment

A comparison between the frequency characteristics of the axial and the mean-spherical sound pressure shows that, for a loud-speaker of the kind here considered, a fairly definite relationship exists. It should be borne in mind that the mean spherical characteristic has been calculated from measurements at seven points only in space, each point being taken to represent the radiation within a division of space. Variations of individual calculations from a smooth curve for the characteristic may not therefore signify more than the degree of approximation obtainable from the limited data.

For the warble-tone tests of average sound pressure in a room, an external influence—the acoustics of the room

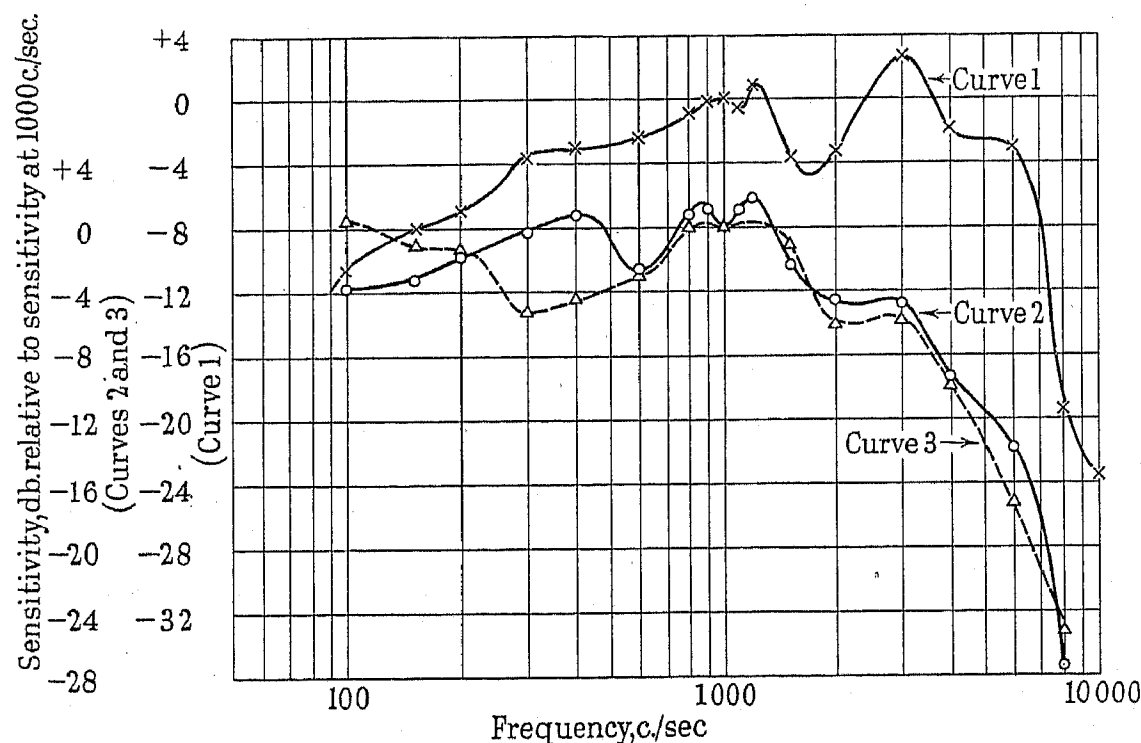


Fig. 4.—Comparison of sound pressures, axial and mean spherical (in free space) and average (in typical room), for Loud-speaker B.

pressures in free space, and Curve 2 shows the mean spherical sound pressures in free space (both measured at a distance of 2 ft.). It will be seen that the curve of mean spherical sound pressures is reasonably uniform from about 150 to 3 500 c./s. It may be said generally to confirm the subjective impression of fidelity obtained from judgment tests. From these two curves were obtained the points represented by circles in Fig. 2, which agree substantially with the relationship between axial and mean-spherical sound pressures found for Loud-speaker A with a more thoroughly soundproofed casing.

—is added; the results are, to this extent, particular to the rooms in which these tests were made. Over a wide middle range of frequencies, substantial agreement was found between the shapes of the characteristics of the average sound pressure in the room and the mean spherical sound pressure in free space. This agreement extended to high frequencies for the tests in one of the rooms, but above about 3 000 c./s. there is some divergence for the tests in the other room, since at these frequencies the radiation tends to become unidirectional and the position as well as the amount of absorption in the room may affect the average sound pressure.

At frequencies below about 200 c./s. a tendency is noticed in both rooms for the average sound pressure to maintain a higher level than does the mean spherical pressure. Such an effect may simply be due to less absorption in the rooms at these frequencies than at higher frequencies. But at these frequencies the wavelengths are becoming comparable with the dimensions of the room, so that considerations which are usual to theories of reverberation in rooms may not fully meet the case. As long as the wavelengths are small by comparison with the dimensions of the room it seems reasonable to suppose that there is an even chance of the sound pressure of the resultant of all the reflected waves being less or more than 90° out of phase with that of the initial wave from a single source; that is to say, there is an even chance of the radiation efficiency of the source in the room being greater or less than in free space. (The radiation efficiency is here identified with the acoustical resistance at the source.) When, however, the wavelengths are comparable with or even greater than the dimensions of the room, it is to be expected that, for a given frequency, there is a greater probability of the radiation efficiency being greater than in free space, and that this probability will tend to increase as the frequency is reduced, until it becomes a certainty when the wavelengths are large by comparison with the dimensions of the room.

It seems, therefore, that at very low frequencies a comparative rise in the radiation efficiency of a source, and hence of the average sound pressure, in a small room is to be expected. This effect would not generally be noticed by a listener in the room, since it is unconsciously recognized as a part of the complicated phenomena which determine the acoustics of the particular room. The effect produced on an original source heard in the room would be similar to that produced on a transmission by loud-speaker in the room.

Such an effect could, however, adversely affect the naturalness of transmission of a single source—in particular, of the speaking voice—by microphone and loud-speaker. For, if the microphone is used in a room which is too small and is inadequately provided for absorbing sound at very low frequencies, the augmentation of response at these frequencies will be transmitted to the loud-speaker and will add to the effect of the acoustics of the listening room in a manner which does not sound natural to the listener.

These considerations have arisen from a study of the test results, but are not regarded as having been established by them. They indicate that it is a wise precaution in any subjective test of a transmission system for faithfulness of reproduction to use a studio which is not only considerably less reverberant than the listening room but also appreciably larger when small rooms are involved in the test.

The general conclusions which have been reached on the question of criteria for performance of a loud-speaker have been summarized above in Section (1).

(3) COMPARISON OF LOUD-SPEAKERS WITH OPEN AND CLOSED CASINGS

The chief departures from conventional construction, in the design which has been evolved from this investiga-

tion, are the use of a closed and soundproofed casing to separate acoustically the front from the back of the diaphragm, and the means for damping the main resonance of the diaphragm. The reasons why these departures were made are the subject of this Section.

(3.1) Theoretical Considerations

While it is recognized that the actual conditions of radiation of sound by a loud-speaker are much too complex for the performance of the loud-speaker to be exactly representable by formulae, it is useful to make simplifying approximations in order that the principles involved may be clearly understood.

Apart from the effects of air-resonances in the casing or of mechanical resonances of the casing (both of which phenomena the design aims to eliminate), it is radiation at the lower frequencies that is most influenced by the nature of the casing in which the loud-speaker is mounted. The simple theoretical argument will be limited to consideration of the low frequencies, and it will be assumed that, at these frequencies, the diameter of the diaphragm is small by comparison with a wavelength and the radiation is predominantly due to simple vibration of the diaphragm, i.e. that any contribution to radiation by complex modes of vibration of the diaphragm is insignificant. The argument will be based on the efficiency of radiation in terms of the total power radiated in free space for a constant force applied to the diaphragm.

For the conditions stipulated, the acoustical radiation resistance R_A at the diaphragm of the enclosed loud-speaker (single source) is proportional to the square of the frequency. If the diaphragm is inertia-controlled, i.e. at frequencies sufficiently above the main resonance, the strength U of the source is proportional to the velocity of the diaphragm and hence inversely proportional to the frequency. The total power radiated ($U^2 R_A$) is thus independent of frequency while these conditions hold.

On the other hand, if the loud-speaker is open at the back, the diaphragm is, at low frequencies, a double source of sound, and the radiation resistance is proportional to the fourth power of the frequency. If the power radiated is to be independent of the frequency, the velocity of the diaphragm must be inversely proportional to the square of the frequency. This requirement cannot be met by any simple mechanical system subjected to a constant force.

The contrast between the open and closed casings, as far as the effect on the movement of the diaphragm is concerned, is mainly a question of the frequency at which the diaphragm resonates. With the open casing, there is no stiffness added to that used for holding the diaphragm in position, but there is an appreciable mass added by the reaction of the air. There is therefore no difficulty in placing the resonance at a very low frequency indeed, though the usual practice with loud-speakers which are open at the back is to use holding devices of greater stiffness than is necessary for mechanical reasons, in order to place the resonance at a low audible frequency where it will give some compensation for the comparative inefficiency of radiation by double source.

The closed casing, on the other hand, adds to the

diaphragm a stiffness which is inversely proportional to the cubic space of the enclosure, and the mass added by the reaction of the air in front of the diaphragm is relatively small. Consequently the size of the enclosure is a main control on the frequency of resonance, and the lower the frequencies for which the desired condition of inertia control applies the larger must be the enclosure. If means are available for providing sufficiently heavy damping of the diaphragm at resonance, then the requirement that the resonance should occur at a sub-audible frequency is not so urgent and the well-damped resonance may be located at or near the lowest audible frequency at which the loud-speaker is designed to operate. This permits the use of a much smaller enclosure.

A rough estimate of the size of enclosure necessary for a loud-speaker to place the resonance at a frequency f_0 is given by the formula

$$f_0^2 = \frac{A^2 \rho c^2}{4\pi^2 m v}$$

where A = effective area of the diaphragm (for the usual type of paper cone diaphragm this area may be estimated as the area of the plane surface bounded by the outer edge of the conical part);

ρ = density of air;

c = velocity of propagation of sound in air;

m = mass of the diaphragm, with coil attached;

and v = volume of enclosed air.

It is assumed that the stiffness of the parts holding the diaphragm in place is small relative to that due to the enclosure. With a paper cone diaphragm of usual construction and about 7 in. diameter, when v is about 0.5 cu. ft. f_0 is about 150 c/s.

With an open casing the size of the casing has most influence on the efficiency of radiation. The nature of this influence can be studied quite simply if further simplifying approximations are made as follows: The front and back faces of the diaphragm are regarded as two equal sources of sound, opposite in phase; the casing separates these two sources by a distance which will be assumed to be equal to the perimeter of the rectangle formed by a path from the centre of the diaphragm along the outer edge of the case and back through the opening in the back of the case, i.e. a distance l equal to the width of the case plus twice the depth. The conditions of radiation of the loud-speaker are thus equated to those of two simple sources, equal in magnitude and opposite in phase, spaced a distance l apart in free air. The object of study is primarily the interaction between the sources from the point of view of phase.

When one source only is sounding in free space the total power radiated is $U^2 R_A$, where U is the strength of the source of sound and $R_A = \rho c k^2 / (4\pi)$ is the acoustical resistance at the source, k being the wavelength constant ($= 2\pi f/c$).

When both sources are sounding simultaneously, the total power radiated is equal to twice the power radiated by either. Thus the total power is given by

$$2U^2 R_A'$$

where

$$R_A' = \frac{\rho c k^2}{4\pi} \left(1 - \frac{\sin kl}{kl}\right)^*$$

The comparison between the power W radiated by the single source (representing the closed casing) and the power W' radiated by both sources (representing the open casing) is simplified by assuming that the strength U is the same in both cases, i.e. that the resonance of the diaphragm is similar in frequency and damping for the two cases. The comparison is then expressed by the ratio

$$\frac{W'}{W} = 2 \left(1 - \frac{\sin kl}{kl}\right)$$

This ratio is plotted in Fig. 5 with the ordinates in terms of kl and also in terms of frequency for the par-

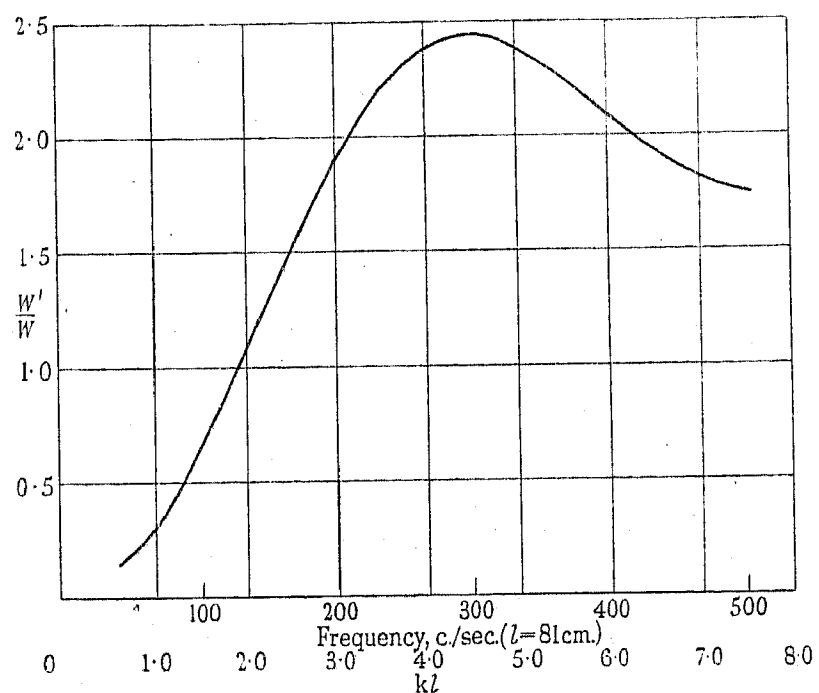


Fig. 5.—Ratio $\frac{W'}{W} = 2 \left(1 - \frac{\sin kl}{kl}\right)$, plotted for values of kl and for values of frequency when $l = 81$ cm.

ticular value of $l = 81$ cm. or 32 in., representing a casing 16 in. wide by 8 in. deep (this size would enclose a volume of nearly 1 cu. ft. of air). Since, as has been demonstrated above, the theoretical value of W is independent of frequency for a simple inertia-controlled system, the curve illustrates the shape of the frequency-characteristic of radiation efficiency to be expected from an open-cased loud-speaker with an inertia-controlled diaphragm acting as a piston. Mechanical resonance is of course generally used to assist in making good the deficiency at the low frequencies.

The first maximum on this curve occurs when kl is about $3\pi/2$ and, unless l has a sufficiently large value, the part of the curve with continuously decreasing efficiency towards the lower frequencies has too wide a frequency range to be satisfactorily compensated by a mechanical resonance. It therefore appears that, with the requirement of a uniform frequency-response in terms of total power radiated, the limitation of size acts more severely on a design of loud-speaker with an open casing than on one with a closed casing.

* See W. WEST: "Acoustical Engineering" (London, 1932), p. 311.

It may also be mentioned that the performance of a loud-speaker having an open case is more likely to be influenced by the proximity of rigid bodies to the opening of the case. For example, in ordinary usage the open back of the case may be placed so near to a wall as to alter the performance quite appreciably.

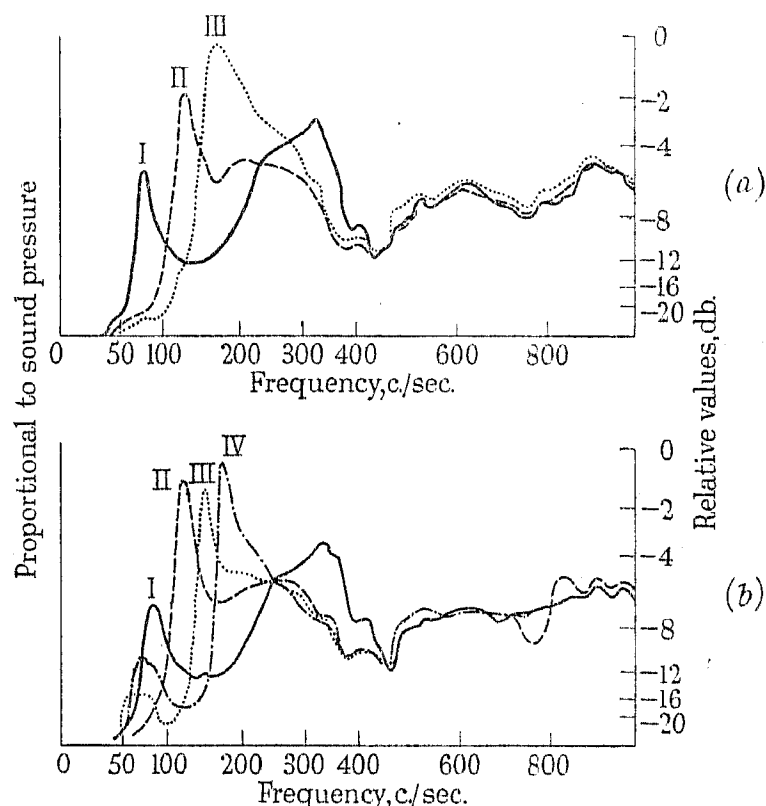


Fig. 6.—Frequency characteristics of a loud-speaker with different types of casing.

(3.2) Experiments in Free-Space Conditions

The method used for obtaining frequency characteristics in free space has been outlined in Section (1.2). A few of the curves taken have been selected to illustrate this Section, and are reproduced in Figs. 6 and 7. These curves are tracings from those obtained by the frequency-characteristic recorder; since the overall sensitivity of the condenser-microphone and amplifier was substantially independent of the frequency, the ordinates of the curves are proportional, on a linear scale, to the sound pressure. All the curves relate to the sound pressures measured at a point on the axis of the diaphragm, distant 2 ft. in front of the loud-speaker.

Where there are differences between the directional characteristics of radiation; there will also be differences in the relationship between the axial sound pressure and the sound power radiated. For loud-speakers in an enclosing case—of the kind here considered—this relationship has been established by experiment [Section (2.3)]; the polar characteristic is approximately spherical at low frequencies, and changes continuously towards a directional beam on the axis at high frequencies. Consequently an axial frequency-characteristic, rising, with increasing frequency, at a rate of about 2.5 db. per octave, corresponds approximately to a uniform power output.

No such relationship has been established for the loud-speaker with an open casing; and in fact the relationship would probably depend more on details of the

construction of the casing. A cross-section of the polar characteristic has the shape of a figure 8 at low frequencies and this kind of shape is maintained at higher frequencies, as long as the obstructions behind the diaphragm permit sufficient radiation towards the back. It is therefore to be expected that, at the lower frequencies, uniform sound pressure on the axis corresponds more nearly with uniform radiated power.

In Fig. 6(a) are shown some frequency characteristics (of sound pressure on the axis) of a commercial loud-speaker unit mounted in an experimental casing. The casing was made of wood in two parts, one movable telescopically within the other, so that the volume of enclosed air could readily be varied. The sides were 12 in. $\times$ 12 in. (internal dimensions) and the back was perforated with a number of holes, each 3 in. diameter, which were sealed by rubber bungs 2 in. thick when the case was closed. The construction was fairly massive, and the walls of the case are regarded as being reasonably soundproof.

Curve I of Fig. 6(a) was taken with the back of the case removed, the depth being 7 in.; Curves II and III were taken with the back closed, the case being empty and enclosing volumes of air of about 0.8 cu. ft. and 0.45 cu. ft. respectively. Curve I shows a shape rather similar to that of the curve in Fig. 5, with the mechanical resonance of the diaphragm at about 75 c./s. superimposed. Curves II and III show chiefly the effect of

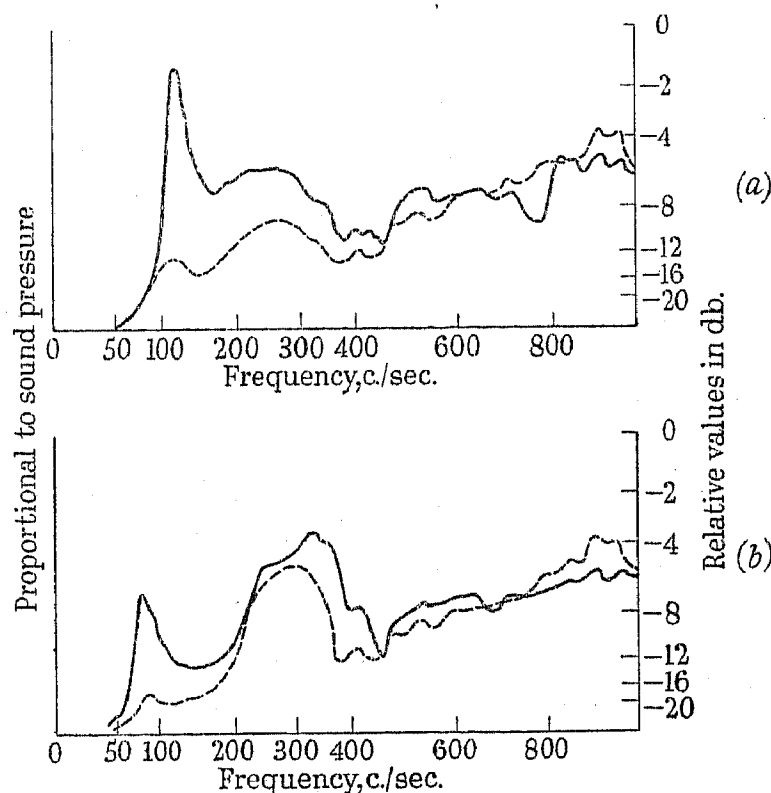


Fig. 7.—Frequency characteristics of a loud-speaker with and without acoustic damping.

(a) Closed casing.

(b) Open casing.

the enclosure in raising the mechanical resonance by the added stiffness of the enclosure. The curves become very similar at frequencies above about 400 c./s.

Fig. 6(b) illustrates the effect of a partial opening of the case by apertures in the back. Curves I and II refer to conditions similar to those to which Curves I and II respectively of Fig. 6(a) apply. For Curves III and IV the back was closed except for one and two, respectively,

of the 3-in. holes being left open. There is here the phenomenon of "double resonance," the mechanical resonator (the diaphragm) being coupled to an acoustic resonator formed by the enclosed air and the openings at the back.* On this and similar evidence it was concluded that a partial opening in the casing does not show sufficient promise to justify further consideration in a design of loud-speaker aiming at a high degree of fidelity.

A useful control of the main resonance of the diaphragm is based on the application of mechanical resistance, or damping. This can conveniently be effected by acoustical means, namely by the application of sound-absorbing material behind the diaphragm. A material such as cotton wool or felt is suitable, and the

frequencies below about 200 c./s. is relatively poor. The region of abnormal sensitivity at frequencies near 300 c./s. is only slightly controlled by damping, as would be expected from theoretical considerations [Section (3.1)].

(3.3) Experiments in a Room

A series of measurements of average sound pressure in a typical living-room was made using a loud-speaker of the type described in Section (5). The measurements took the form of a direct comparison of the average (i.e. the most probable) sound pressure set up by the closed-case loud-speaker in Room X with the average sound pressure set up in the same room by the same loud-speaker operating with the back of the case removed.

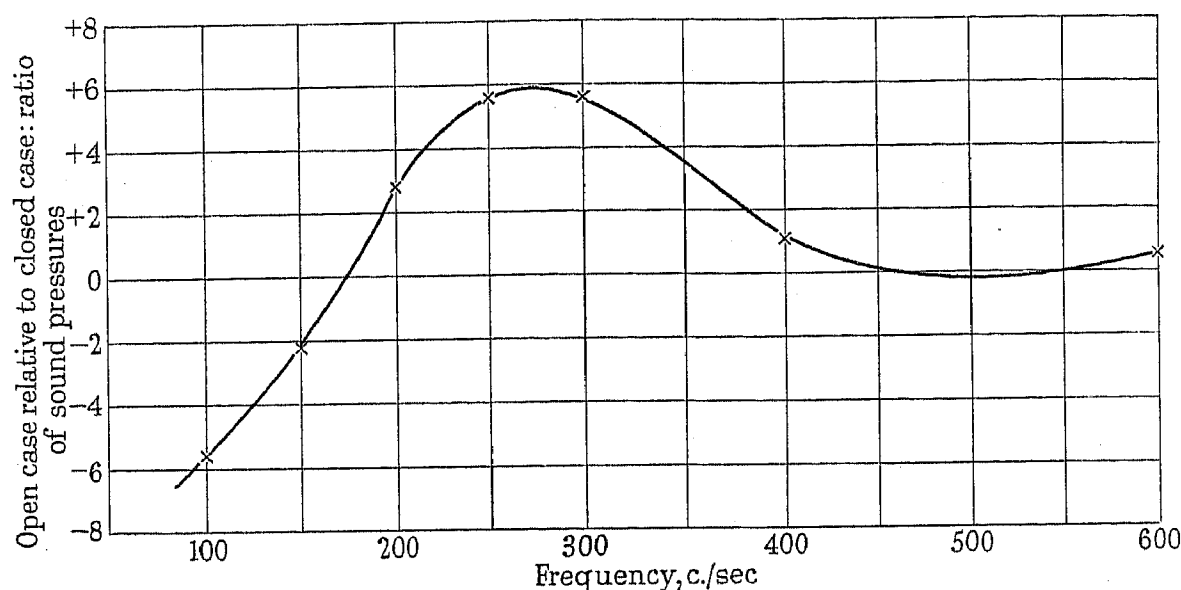


Fig. 8.—Comparison of average sound pressures in typical room for loud-speaker in closed case and in case open at back.

extent of damping can be varied, e.g. by varying the thickness and density of the covering. For maximum effect the absorbing material should be placed near the diaphragm, where the movement of displaced air is greatest.

This control is illustrated in Fig. 7(a) for the enclosed casing and in Fig. 7(b) for the open casing—as used for Curves II and I respectively of Fig. 6(a). In Figs. 7(a) and 7(b) the full-line curve refers to the condition with no damping, and the broken curve to the addition of damping by cotton wool, about 1 in. thick, wrapped round the back of the loud-speaker unit.

With the enclosed casing (Fig. 7a) the damping is sufficient practically to eliminate the effect of resonance, so that the resonance frequency can remain in the audible frequency range, with the result that a much smaller casing may be used than would be necessary if the resonance frequency were to be placed at a sub-audible frequency. The curve with damping approximates, in fact, to the ideal presented by the objective criterion that is being used [Section (1.2)].

With the open casing, while the effect of resonance is also substantially reduced, the resulting frequency-characteristic is not so uniform and the response at

* The natural frequency of the acoustic resonator, acting alone, can be estimated to be about 100 c./s. with one hole open, and about 140 c./s. with two holes open.

The technique of measurement was in conformity with that described in Section (2.2). The loud-speaker was placed successively in each of several positions in the room, being operated first with the back of the case in position and then without the back. A total of 64 observations of sound pressure over the range of low frequencies (100 to 600 c./s.) was made for each of these operating conditions and the difference in the average sound pressure resulting from the removal of the back of the loud-speaker was calculated. The results, which are plotted in Fig. 8, confirm, in general form, the findings of the theoretical investigation [Section (3.1)].

(4) FACTORS AFFECTING THE PERFORMANCE OF THE LOUD-SPEAKER

The design of the loud-speaker of which a broad constructional specification is given in Section (5) incorporates, wherever possible, the well-known features of modern moving-coil type loud-speakers. Advantage was taken of the great skill and experience which has been acquired by manufacturers, in order that a cheap and efficient product could become available, without avoidable necessity for laying down expensive additional plant. Departures from usual construction have there-

fore been made only where experiment indicated that sufficiently improved quality of performance would result therefrom, and where the modifications involved appeared to be feasible from the constructional point of view.

In this section are summarized the influences, affecting quality of performance, of the various parts which make up a moving-coil loud-speaker, as they have been confirmed or revealed by the experiments. No modifications have been made which affect appreciably the sensitivity, except that any elimination of pronounced resonances tends to reduce the sensation of loudness of transmitted sounds. The discussion is concentrated on frequency distortion, since no evidence has been found that non-linear distortions of well-designed modern loud-speakers exert any comparable adverse influence on the quality, at volume levels suitable for an ordinary living-room.

(4.1) Magnet

No unexpected features of the effects of magnet design on the performance have been sought or encountered. Most of the experiments were made using a permanent magnet of about 170 cm³ overall size, generating about 6 000 lines per cm² in an air-gap of 1.075 in. external and 0.98 in. internal diameter and 0.25 in. deep.

(4.2) Coil and Coil-former

No substantial evidence was found that commercial methods of construction of coil and coil-former impose any limitation on the performance of the loud-speaker. Additional stiffening of the coil former was not found to make any appreciable change in the frequency characteristic.

Simple auxiliary precautions towards ensuring true axial movement of the coil in the air-gap are: (i) taking out the leads to the coil at opposite ends of a diameter, to ensure symmetry of the mechanical load due to the leads; and (ii) taking out the leads at the same winding level, i.e. winding an even number of layers. This eliminates any resultant current in the coil, in the direction of the axis, which could set up forces tending to twist the coil.

(4.3) Centring Devices

Both centring devices, commonly known as the "spider" and the "surround," add to the moving system a very small mass and a stiffness which may be, but need not be, appreciable. It is common practice so to adjust the combined stiffness that the main resonance of the moving system lies at the lower extremity of the frequency range which it is desired to transmit. At lower frequencies the efficiency of the loud-speaker must necessarily fall off rapidly, especially when an open casing is used.

For the design of a loud-speaker to be used in an enclosed casing, it is desirable that the contribution of the centring devices to the total stiffness should be negligible. The limitation of the frequency range at low frequencies is then determined by the size of the casing.

The stiffness due to the surround can be quite small with the cloth surrounds that are sometimes used. An alternative construction, which introduces still less stiff-

ness and mass, is available by replacing the usual type of surround by an air-gap between the diaphragm and the frame, bridged at a limited number of points (say three, spaced equally round the diaphragm) by straps of tape which support the diaphragm. Each strap is fixed at one end to the diaphragm and at the other end to the frame, with a distance of, say, 0.5 in. separating the fixing points. With this construction the rim of the diaphragm should be made sufficiently rigid, e.g. by forming a circumferential corrugation near the edge. The influence of the air-gap between the edge of the diaphragm and the frame is not appreciable for widths of the air-gap up to at least $\frac{1}{8}$ in., for a diaphragm of about 7 in. diameter.

With a rather small enclosed case, limiting at about 100 c./s., many types of external spider in current use introduce a stiffness which is not very appreciable. With a larger case, however, limiting at 40 or 50 c./s., a spider of reduced stiffness, e.g. of thinner material, is required.

Under the influence of the forces vibrating the moving system the spider is liable to vibrate, at certain impressed frequencies, in a mode of vibration, having a natural frequency other than the impressed frequency. This gives rise to audible false tones from the loud-speaker at the particular frequencies concerned. The effect appears to be more marked when there is tension in the spider.

(4.4) Framework

This part should not affect the performance of the loud-speaker, but with some commercial constructions it has been found that the apertures in the framework are insufficient to provide complete freedom of movement of the air behind the diaphragm. In such cases it appears that the resonator formed by the air cavity between the diaphragm and the frame in conjunction with the apertures in the frame acts as an anti-resonator on the output of sound by the diaphragm. This can reduce the efficiency of the loud-speaker somewhat over a range of frequencies, say 1 500 to 2 000 c./s., where there is generally some difficulty in maintaining the efficiency of radiation of sound by the diaphragm.

In the design which results from these investigations the effect has been eliminated by limiting the part of the framework between the inner plate (attached to the magnet) and the outer rim to four strips each $\frac{3}{4}$ in. wide.

(4.5) Casing

For reasons given in Section (3) the investigations have been concentrated mainly upon loud-speakers with an enclosed case. The influence of the size of the case on the response at low frequencies has been discussed in Section (3). The compromise between size of loud-speaker and limitation of response at low frequencies having been decided, it remains to devise a construction of the case which is adequate for soundproofing and at the same time economical in space and cost.

Two main principles for soundproofing are generally recognized; one is the use of massive non-porous walls, preferably of a material of a non-resonant nature, such as lead. The other is the use of composite walls consisting of alternate layers of non-porous material and

separating layers or pads of vibration-insulating material, such as soft rubber or felt, the mechanical properties of the different layers being very dissimilar.

A number of different constructions were tried, of which the following was considered to be the most generally satisfactory for a reasonably inexpensive product with external dimensions about 15 in. $\times$ 15 in. $\times$ 8 in.: The outer wall of plywood $\frac{3}{8}$ in. thick; the separating layer of felt $\frac{1}{4}$ in. to $\frac{1}{2}$ in. thick, of the kind used as an underlay for carpets; the inner layer of corrugated cardboard, of the kind used for packing, assembled with the corrugated side inwards. A further slight improvement in soundproofing results from the insertion of a sheet of thin lead between the felt and the cardboard in the back wall of the case which, having the largest area of all the walls, is the most vulnerable to penetration by sound. The layers of felt and cardboard were not found to be necessary on the front wall, which carries the relatively massive load of the loud-speaker unit.

The fixing of these soundproofing layers by glue was found to have a detrimental effect, and it is not necessary. When the cardboard is jammed into position its stiffness is practically sufficient to hold the linings in place, and the use of a few light tacks from the cardboard through to the wood ensures firm fixing. This treatment also provides a useful degree of absorption of sound within the enclosure.

The sound-absorbing covering over the back of the loud-speaker unit may be regarded as part of the casing. Two layers of the same kind of felt as are used for the lining were found to be required to give the most nearly correct frequency characteristic—according to the objective criterion stated in Section (1.2). Where size of the loud-speaker is a less important consideration, an even response down to lower frequencies can be obtained by using a larger casing. Since the surfaces are greater and the frequencies of effective response are lower with a larger casing, somewhat more soundproofing is desirable, e.g. greater thickness of wood and of lead and an additional layer of felt between the lead and the cardboard.

A casing in the form of a cube with 16-in. edges (external) gives good response down to about 50 c./s., and this is used (with the design otherwise unchanged) for special purposes where best quality is required. It was used, in conjunction with a special high-frequency sound radiator, giving reinforcement at frequencies above about 4 000 c./s., for the fidelity tests mentioned in Section (1.1).

(4.6) Diaphragm

While the stiffness of the centring devices and the construction of the casing exert the greatest control on the performance of the loud-speaker at low frequencies, it is on the characteristics of the diaphragm, or cone, that the performance at other frequencies depends.

Some previous experience with commercial loud-speakers had shown that the cone supplied with a certain individual make of loud-speaker was capable of producing an exceptionally uniform characteristic of approximately the shape required—up to about 3 500

c./s. It was discovered that this cone (hereinafter referred to as Type A.1) had been manufactured abroad, but the manufacturer of the loud-speaker (Manufacturer A) had installed plant for manufacturing cones and was willing to co-operate in producing an equivalent, or if possible an improved, type of cone.

Only a few examples selected from the very large number of frequency characteristics obtained with different diaphragms can be reproduced here. Each of these curves (Figs. 9 to 12) was taken on the axis of the diaphragm at a distance of 2 ft. from the front of the loud-speaker. In each case the diaphragm was assembled with an outer centring device of 3 tapes [Section (4.3)] in an enclosed case. Since the curves were taken at different times throughout a long investigation the cases and mountings used were not always the same, but the differences involved would only affect the low frequencies (below about 300 c./s.). On each chart is also shown for comparison a standard curve which represents the design objective for the axial frequency-characteristic of a loud-speaker of this type [Section (1.2)]. The standard curve is that for a sound pressure rising at a uniform rate of 2.5 db. per octave—as it would be recorded by the equipment that was used for taking the records. This equipment is approximately equalized, so that the ordinates of the curves are roughly proportional to sound pressure for frequencies from about 100 to 5 000 c./s.; at higher frequencies the sensitivity of the equipment falls away—to the extent shown by the deviation from rectilinearity of the standard curve.

The equipment is provided with different frequency-ranges, of which the range 0–5 000 c./s. (Figs. 9 and 11) was often used since it covers the frequencies of greatest practical interest for the present purpose [see last paragraph of Section (1.2)]. The range 0–9 000 c./s. (Figs. 10 and 12) was also very generally used.

The curves in Figs. 9 to 12 are, like those of Figs. 6 and 7, direct reproductions of the curves taken off the drum of the recorder; they therefore show all the minor irregularities in complete detail. A scale converting the linear law for the ordinates into relative values in decibels has been added to the curves.

Diaphragms supplied by Manufacturer A.

The full-line curve in Fig. 9 is typical of the performance of the A.1 type of diaphragm. This is a moulded paper cone, to all appearance of quite usual construction. The shape and dimensions of this cone are also shown on the same sheet, and these apply equally to the diaphragms to which Fig. 10 refers.

In attempting to obtain an equivalent performance the manufacturer first submitted a number of samples, all of which were true copies in size and shape but different in some details of manufacture. One of the worst of these samples—as judged by comparison with the standard curve—is the one designated A.2 and shown by the broken curve in Fig. 9. A curve of this general shape has been very frequently encountered during the investigation.

Based on these tests the manufacturer then submitted a second batch of samples made with further small modifications of manufacture; and the full-line curve,

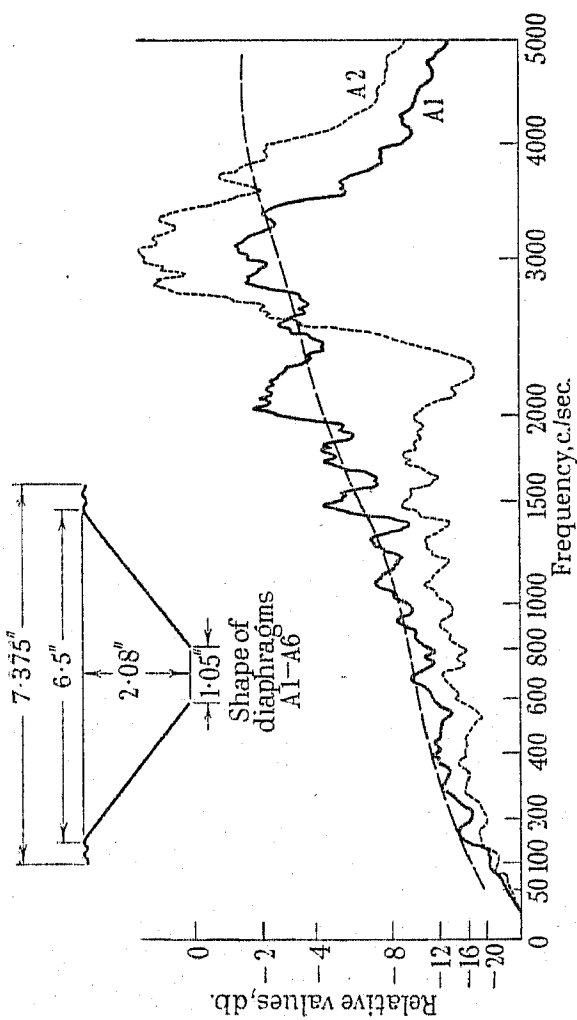


Fig. 9.—Comparison of diaphragms A.1 and A.2.

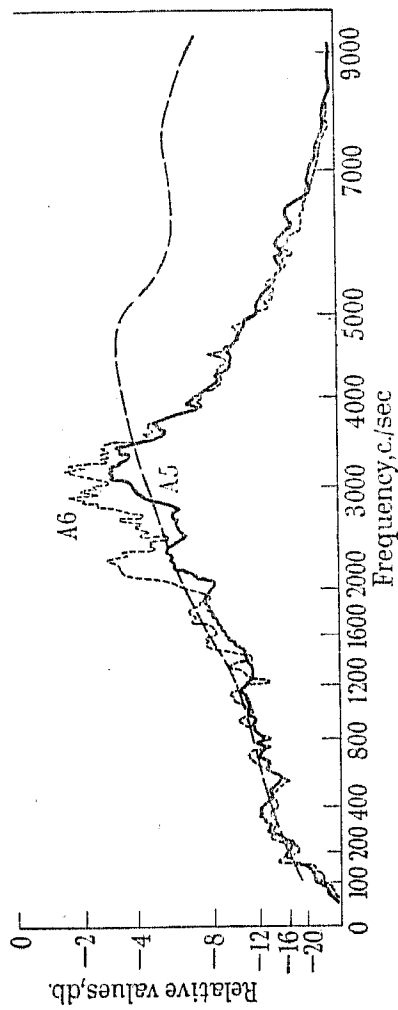


Fig. 10.—Comparison of diaphragms A.5 and A.6.

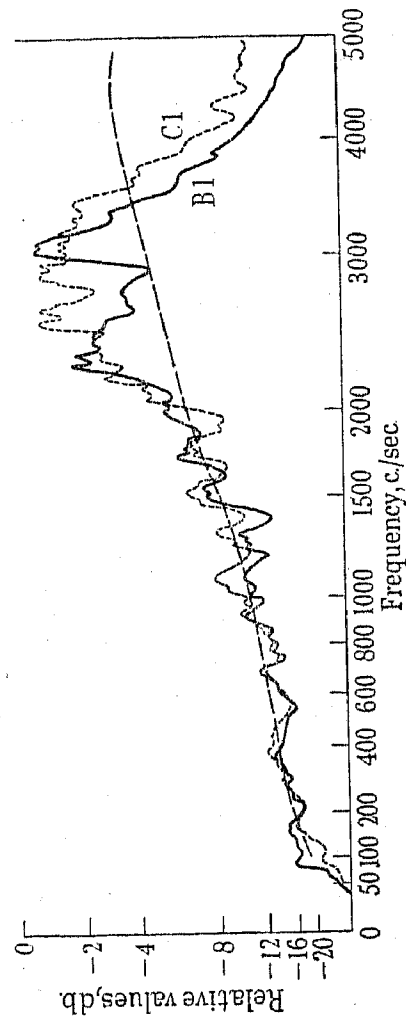


Fig. 11.—Comparison of diaphragms B.1 and C.1.

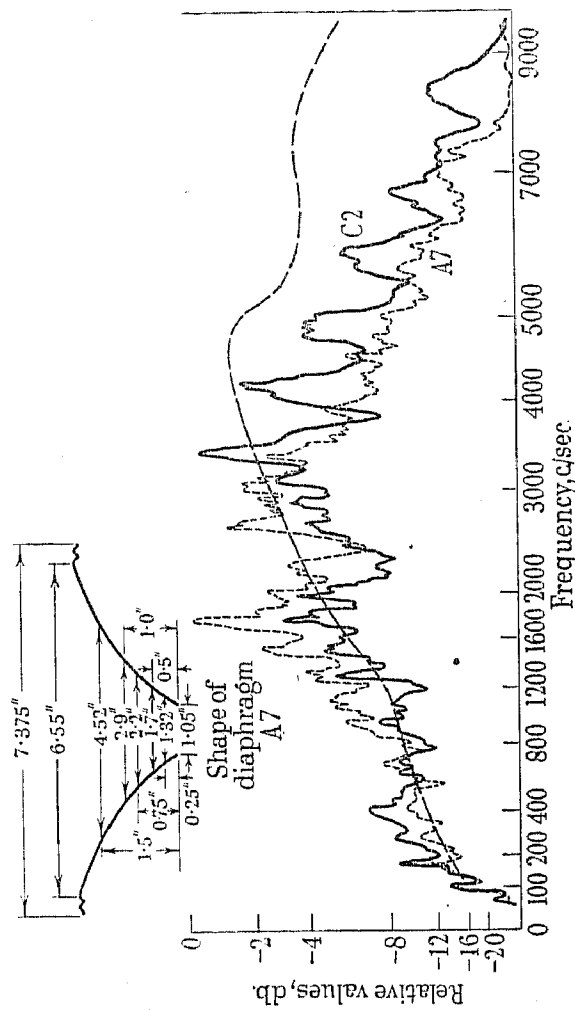


Fig. 12.—Comparison of diaphragms C.2 and A.7.

A.5, of Fig. 10 is typical of samples submitted later as direct manufacturing copies of the best sample of this second experimental batch.

Further experiments were made, but no further improvement has so far been obtained. Work on these lines, involving a close co-operation with manufacturers, could usefully be continued. The broken curve, A.6, in Fig. 10 is typical of more recent supplies which have a different code number but are probably of very similar manufacture.

A few of the samples have been subjected to chemical analysis and mechanical examination. None of these tests, except perhaps a breaking test, gave any differentiation between cones which were comparatively good or bad as regards performance. There was a general tendency for the better cones to give lower breaking-load figures for samples 1 in. square cut from them, though such figures can be very variable as between samples from the same cone.

Some particulars relating to the cones to which Figs. 9 and 10 refer are given in the Table. With regard to the manufacturer's code number, the figure following the stroke (e.g. "65" in "9772/65") gives the weight of the cone, in grains. This figure includes the weight of a flat surround extending to a diameter of 8.3 in. which is cut away for assembly by the 3-tape suspension.

Table

Cone No.	Manufacturer's Code No.	Approx. thickness	Breaking load for 1-in. sample
A1	—	mils 15	lb. 10-15
A2	9772/65	10	18-35
A5	9815/58	13	12-15
A6	9981/49	—	—

Diaphragms supplied by other manufacturers.

A considerable number of diaphragms from the stock of other manufacturers has been tested, but only those were selected which were of suitable size and shape for mounting in the experimental loud-speaker unit. Record is made here of only the few samples whose performance approximates to the standard desired.

Diaphragm B1, shown in Fig. 11, is not moulded but formed from flat sheet paper into a straight cone, without corrugations. It is normally mounted with a cloth surround—in which condition it was tested. This cone is heavier than most moulded cones, and the main resonance is therefore at a somewhat lower frequency.

Diaphragm C1, also shown in Fig. 11, is the best example of the straight-sided cone diaphragms (moulded) obtained from Manufacturer C. A number of diaphragms obtained from this manufacturer were moulded with circumferential corrugations, and the general characteristic of these diaphragms was an emphasis of the mid-frequency range, the greatest ordinate of the curve lying, in most cases, between 1 000 and 2 000 c./s.

An interesting variation in shape is provided by forming the diaphragm with a flare. A diaphragm of such shape is represented by the curve C2 in Fig. 12, a

feature of this curve being the relatively greater efficiency obtained at the higher frequencies, though the irregularities are more pronounced throughout the range than with the best of the straight cone diaphragms. An attempt was made to obtain the advantage of better response at high frequencies with less marked irregularities, and some samples of flared diaphragms were obtained from Manufacturer A. The performance of one of these is shown by Curve A7 in Fig. 12.

It was not considered that advantage was gained by the use of this type of diaphragm, and circumstances did not justify proceeding with the experiment. At the same time, the experiment shows that there is some promise of obtaining improvement of response at higher frequencies—without sacrifice of performance over the main frequency range—by a suitable shape and manufacture of flared diaphragm.

(5) AN OUTLINE OF THE SPECIFICATION RESULTING FROM THE INVESTIGATION

This Section deals with the specification which was suggested as a result of the experiments. On it was based a commercial specification which was issued to a number of interested contractors. Latitude is allowed to the contractor over details which are not considered likely to affect the performance, e.g. the shape and size of the magnet. An outline of the specification follows.

The loud-speaker may be considered to consist of two main parts, namely the case and the loud-speaker unit.

(5.1) Case

The construction of the case is illustrated in Fig. 13. The case consists of a box of $\frac{3}{8}$ -in. plywood with an aperture 8-in. diameter in the front. The two sides and back are lined with each of the following:—

- Felt (about $\frac{1}{4}$ in. thick);
- Lead sheet (8 oz. per sq. ft.);
- Corrugated packing paper (with the corrugations inwards).

The top and bottom are lined each with rectangles of the felt and corrugated paper, which serve to hold the linings on the sides and back into position. No adhesive should be used; two or three light tacks through the linings of the top and bottom only should be used to retain the linings in position.

Two layers of felt on the back of the front panel are held round the aperture to form a bag surrounding the back of the loud-speaker unit, when in position.

(5.2) Loud-speaker Unit

Magnet.

Permanent magnet, not greater than about 250 cm³ total size, developing at least 6 000 lines per cm² in an air-gap of 1.075 in. external and 0.980 in. internal diameter and 0.25 in. deep.

Frame.

Suggested construction is illustrated in Fig. 14.

The exact depth of the frame should be adjusted to position the coil correctly in the air-gap. Excessive

obstruction behind the cone is to be avoided; for this reason the four bars connecting the outer ring to the inner part (which is secured to the magnet) are limited to $\frac{3}{4}$ in. width.

Coil.

Total of $53\frac{1}{2}$ turns in two layers of $26\frac{3}{4}$ turns each, of 0.0092-in. diameter enamel-covered copper wire. Ends of winding secured to former and left sufficiently long for connection to insulated soldering points (not illustrated) on the frame. The free lengths of these wires to be covered with cotton sleeving.

Edge suspension.

The outside diameter of the cone is $7\frac{3}{8}$ in. The clearance from the inner edge of the outer ring of the frame ($7\frac{1}{2}$ in. diameter) is free except at three points where strips of unstretched tape, $\frac{1}{4}$ in. wide, cemented at their ends to the cone and to the outer part of the frame respectively, comprise the suspension.

Stiffness of suspension.

The resonance frequency of the unit should be determined, before assembly in the case, by applying a

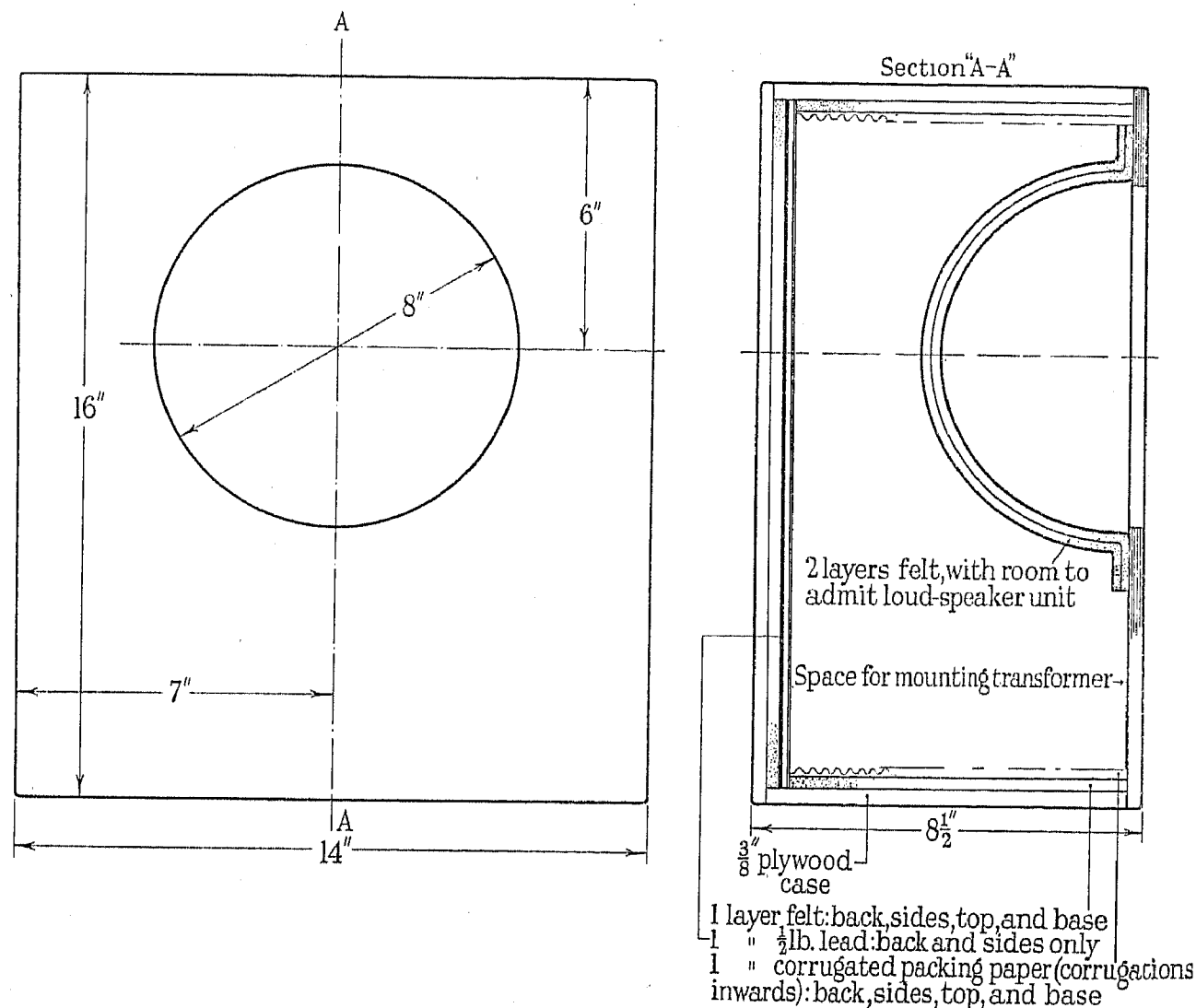


Fig. 13.—Construction of case for loud-speaker.

Spider.

Stiffness imposed by the spider to axial movement of the cone should not be excessive (see final paragraph of this Section). This can usually be achieved by the use of sufficiently thin material, irrespective of the shape and manner of fixing of the spider.

Cone.

At present it is only possible to specify one make of cone, namely Type 9881/49, supplied by Manufacturer A.

In view of possibilities of variations of supplies it will be required initially that 1 per cent of cones obtained for use in the Post Office Engineering Department's contracts shall be tested by the Department for acceptance.

constant p.d. of variable frequency to a circuit consisting of the coil of the loud-speaker unit and a resistance of 5 ohms, and by observing the frequency at which the p.d. across this resistance of 5 ohms passes through a minimum value. The frequency of resonance so determined should not be greater than 30 c./s.

(6) CONCLUSIONS

On the question of how to judge the quality of loud-speakers, the authors consider that the criterion of faithfulness of reproduction, comparing a variety of types of sound reproduced by the loud-speaker with the original sources, heard in the same room, cannot be improved upon. The room should, of course, be of a kind similar to that for which the use of the loud-speaker is intended, and the types of sound should be restricted

sample experienced by the listener L_1 to the original source of sound S when this is reproduced through any reproducing system M, A, R , it is necessary to compare aurally these two acoustic fields in such a way that the fickle memory of the ear is eliminated. It is likewise not entirely theoretically sound to try to have a duplicate source of sound in the reproducing chamber, chiefly because reproducing rooms are uncontrolled in that their period of reverberation is greatly different from the optimum for the type of material reproduced; no attempt is generally made to distribute the radiated sound in such a way as to simulate optimum conditions. To investigate whether such samples of original and reproduced sound can be made comparable, especially by shifting the microphone M of the reproducing system, it is clearly necessary to have two exactly similar microphones located at M_1 and M_2 and the outputs switched, preferably without breaking the circuit, through a high-grade reproducing system A_1 , of quality at least equal to that of the system under test. The comparison system must clearly be highly free from blur of any kind and the listening must be on telephones, otherwise an additional reverberation blur would swamp any similar blur in the system under test. Such an aural comparator system, with two chambers, each about 4 000 cu. ft. in volume, with adjustable reverberations, T_1 and T_2 , between about 0.6 and 3 sec., has been in use for some years at the City and Guilds College; under academic conditions this type of fundamental research is necessarily slow, but some results will shortly be published. The comparison microphones are moving-coil, such as were generally used by the B.B.C.; the head-telephones are also moving-coil. With this system the reverberation responses of various types of microphones and radiators can be studied subjectively, and the validity of technical criteria verified. To test one acoustic point, a pair of matched voices was discovered and used along the lines suggested by the authors, but this cannot be accepted as a general method. Using the comparison method it is generally possible to make good aural balances; it is actually a delicate adjustment and the listener must move the microphones remotely with strings. Once obtained, the balance is quite certain.

Although contrived long after the method of subjective assessment of the quality of reproduction of radio receivers for schools, as operated by the Approval (Apparatus) Sub-Committee of the Central Council for School Broadcasting, the latter's method is directly deducible from the theoretical method outlined above, except that the so-called standard radio receiver, which is properly used as a reference, replacing M_1 (there being a radio link in both test and reference circuits), is not of the highest quality obtainable, so that the testing committee of non-technical teachers can more easily decide where, on their subjective scale, the test receiver falls into place.

Mr. A. J. King: There is one feature of moving-coil loud-speaker design which appears to me to be very important from both the magnetic and acoustical points of view, and yet which seems to have been decided rather arbitrarily in the paper. I refer to the diameter of the moving coil, which is given as approximately 1 in. From the magnetic point of view a larger diameter is preferable,

especially if a centre magnet of Alnico is used. This arrangement with a soft-iron yoke and pole-faces gives a good design with very low leakage if the gap mean diameter is of the order of 3 in. Such a diameter gives sufficient cross-section of Alnico to use it efficiently at its low operating flux density of 4 500 without the necessity for tapering the magnet down to the gap, a procedure which increases the leakage. For example, a centre pole 3 in. diameter and $\frac{1}{4}$ in. wide can be fed by a centre magnet $2\frac{3}{4}$ in. diameter with a 1-in. hole for convenience in assembly. The length of magnet naturally depends on the air-gap. From the acoustical point of view there is very little objection to the use of a coil of 3 in. diameter. The loss of area in the middle of even the small $7\frac{1}{2}$ -in. cone described is a small percentage of the total area and is offset somewhat by a reduction in weight. The stress on the junction between moving coil and cone is reduced for a given output to approximately one-third. In addition the side of the cone is appreciably shorter and stiffer.

The arrangement has been tried and leads to a very sensitive loud-speaker which maintains its output to higher frequencies than with the same cone material and a small moving coil.

As regards sensitivity, a convenient check over the range where inertia-controlled piston movement can be assumed is one I described some years ago.* It consists of turning the loud-speaker so that its axis is vertical, and determining the minimum direct current through the moving coil which will just support the weight of the cone and coil. If this current is I mA and the projected area of the cone is A cm², it is easy to show, with the above simplifying assumptions, that the r.m.s. sound pressure developed at 1 m. from the cone per mA (r.m.s.) input to the coil is $0.0019 A/I$ dyne/cm²/mA. There are obviously many factors of which this takes no account, but it is a good criterion of sensitivity in the medium-frequency range.

Flight-Lieut. M. G. Scroggie: Referring to the authors' subjective criterion of performance (Section I.1), a programme sound which is heard directly is modified by the acoustics of the listening room. It will therefore be agreed that, when listening indirectly by means of a reproducing system that is perfect, the aural impression is as nearly as possible identical with the original when either studio or listening room *but not both* is acoustically similar to the direct listening room. The authors choose to introduce the acoustical effects at the listening end, the studio being "dead." At first sight this sounds reasonable, because in general it is more practicable for the studio to be controlled in this way than the domestic listening room. But in choosing thus, the authors have had to rule out just those types of programme that present the most interesting and complex problem in high-quality reproduction. The acoustical influence of surroundings is one of the dominant factors in the aesthetic enjoyment of programmes, making all the difference between a depressing experience and an inspiring one. It compensates also, in substantial degree, for loss of vision in dramatic broadcasts. It is only at the studio end that the necessary variations can be introduced. For testing purposes it is in general easier for the listener to move

* *British Radio*, 1929, 2, p. 76.

himself from a studio, which is either the direct listening room or its equivalent, to a "dead" indirect listening room, than to transfer the source of sound as described in the paper. The former method enables the comparison to be carried out with all types of programme, including dramatic or large-scale concert performances.

In studying the influence of the listening room, tests were carried out in rooms described as typical but which seem to be decidedly exceptional both in shape and size. A height of 11 ft. 6 in. must be well above the average for domestic rooms, and volumes approximately half of those specified would probably be nearer the average.

In the formula for calculating the mean spherical sound pressure (Section 2.1) it would appear to be more satisfactory to select test angles which would give *equal* concentric divisions of space. It is not clear that there is any justification for giving so much less weight to the data for axial radiation than to others.

The exclusive concentration on frequency distortion in loud-speakers is at least open to question. The ear must necessarily be very tolerant of frequency distortion, because of the very large variations in frequency characteristics introduced by the acoustics of different listening rooms. On the other hand, the ear is extremely sensitive to alien tones. A slight "buzz" in a loud-speaker renders reproduction well-nigh intolerable yet may not be revealed at all by a frequency test. Moving-coil loud-speakers of typical construction have often been shown to introduce frequency-halving, frequency-doubling, and transient distortion due to oscillatory "hangover." In this connection one could wish that the authors had not entirely ignored the impedance out of which the loud-speaker has to work.

Finally, with reference to the last paragraph in Section (6), the authors' views on the double-cone type of construction for improving high-note response would be welcomed.

Mr. D. R. Turner: The authors have utilized what they consider to be a typical living-room, and by means of tests carried out in it have arrived at certain conclusions as to the most desirable characteristics for loud-speakers for use in living-rooms. However, the room chosen for this purpose was considerably larger than the majority of living-rooms and I would suggest that a room 15 ft. by 12 ft. by 9 ft. high, or slightly smaller, would be more "typical." In view of this do not the authors consider that it would be advisable to carry out supplementary tests in a smaller room in order to determine whether the room size will materially modify the speaker characteristics required for faithful reproduction?

It is stated that the object of the investigations was to design a speaker which would, among other requirements, be inexpensive, and that samples submitted by contractors were satisfactory both as to performance and price. As the price of loud-speakers varies over a very wide range, it would be interesting to know into what portion of this range the prices of these samples fall.

The bad practice of fitting the radio receiver and loud-speaker in one cabinet is not mentioned in the paper. Do the authors consider that the evil effects of this practice could be lessened to any extent by the use of damping materials in the cabinet?

Mr. P. G. A. H. Voigt: The experience that abnormal

room acoustics can have a surprising effect is one that is often encountered when demonstrating high-quality reproducing apparatus, and is also familiar to organ builders, who usually "voice" their instruments on site for this reason. It is unfortunate that many modern rooms with hard plaster surfaces and therefore excessive treble reverberation have cavity walls which absorb the bass, thus aggravating the trouble. The thick walls covered with soft plaster often found in old houses have the reverse effect, especially if the room is heavily carpeted, has upholstered furniture and heavy curtains. In this connection it is important to note that with a defective reverberation curve the energy relation of different frequencies will change as a note decays. "Cooking" the frequency response of the amplifier, etc., can only be regarded as a useful method of partially hiding one fault by introducing another; it can never be a real cure, since no amount of "cooking" can prevent the change in tone colour as a sound dies away.

When calibrating, even with a warble tone, violent differences in loudness are to be expected as between different positions under live conditions, especially at the lower end of the frequency spectrum. That an average of 9 readings may differ from an average of 54 by as much as 10 db. is, however, very surprising, and I hope that the authors can give us more information about these special cases. In view of the fact that the 9 positions in the frame are geometrically related, it seems feasible that at certain low frequencies their pattern may happen (especially if near the walls) to fit the mean stationary wave pattern of the warble tone. If under such conditions all 9 positions are situated simultaneously in nodes or antinodes for stationary-wave patterns in different directions, the most violent departures from average loudness could occur.

Another possibility is that the frame might correspond to the average listening position, i.e. in front of the loud-speaker near the axis, and therefore come within the high-frequency beam. Measurements in this position would naturally show a treble response considerably above the average.

It is my experience that the actual response in the direction of the listener has some effect, and that the comfort of listening is greatly enhanced if concentration of high frequencies is prevented, so that direct and reflected sounds approximate in composition. It is a pity that various considerations (presumably, mainly that of cost) prevented the inclusion of means for spreading the beam, thus compelling the study of a system which is inherently "beamy" and can therefore never become perfect no matter how carefully the relation between axial and average response is established.

I hope that the authors will stress the fact that the characteristic which they have deduced, namely a slope of $2\frac{1}{2}$ db. per octave, is only an approximation which happens to fit their particular dimensions fairly closely. Actually, as they say on page 439, Section (3.2), the radiation is spherical at low frequencies. At these frequencies, therefore, the axial response will equal the average response, and if this latter is uniform the axial response will be uniform also. This is confirmed by the readings below 300 c./s. plotted in Fig. 2 (crosses), which lie nearly on a horizontal line. If the curve is

drawn through these points, i.e. zero slope per octave up to 300 c./s., and then continued through the other points it will curve upward (in a region actually determined by the dimensions of the sound source) and then rise more steeply than $2\frac{1}{2}$ db. per octave. The true curve relating axial to total radiation is therefore more complicated than a single straight line. Between 100 and 3 000 c./s., however, a line sloping at $2\frac{1}{2}$ db. per octave lies so near the more complicated curve that the authors are quite justified in adopting the simpler curve for their particular purpose.

The curves published are taken with constant voltage on the grid of the power valve. Under laboratory conditions a triode whose internal resistance might be about one-quarter the optimum load would probably be used. With a pentode, the curve would be different unless the impedance curve (not published) happened to be level. I should like to have some more information on this point.

It is usual for a loud-speaker impedance curve to rise considerably in the bass; this mismatching (when used with triodes) causes the speaker to reject low frequencies and may account in part for the fact that in spite of a resonance as low as 30 c./s. the output diminishes rapidly below 100 to 200 c./s.

With regard to the design of the coil, the use of an extra half-turn would seem to introduce a lop-sided factor, because that half of the coil with the extra half-turn, although heavier, would be subject to increased forces. The effect of the extra force could be avoided by winding the additional half-turn on the speech-coil tube outside the gap. From the fact that the authors have not found this necessary, I take it that the effect is negligible.

The spider is mentioned as a possible source of trouble. One manufacturer has used damping pads, presumably to prevent this. Have the authors found anything special to be necessary?

Their experience with various apparently similar cones, is most interesting. I have found that the surround may have a marked effect of a similar kind at high frequencies, and have therefore concluded that wave reflection up and down the cone can occur. If the material of the cone itself can be made to absorb energy, such a stationary wave would be damped. I should therefore be interested to know whether any experiments are contemplated to ascertain whether differences in internal damping of the cone material account for the differences in response experienced between apparently similar diaphragms.

No mention is made of the preferred position for the loud-speaker. I think that it is most undesirable to have it near the floor. What is the authors' opinion?

Finally, are any steps taken to prevent the felt from becoming a breeding place for moths, and if so does the treatment affect its sound-absorbing properties?

Messrs. A. K. Webb and R. C. G. Williams: The authors have published a paper which will be of value to all those interested in the art of reproduction, both in view of the novel features embodied in the design and the original angle from which the problem has been approached. We have, however, a number of comments to make, based on practical experience, which

can conveniently be grouped under four headings as follows:—

(A) *Variation of response with position of observer.*

The design of the loud-speaker unit described in the paper is based on the assumption that acoustic power output should be constant throughout the frequency range considered (for a constant input). We agree in general with this conclusion, but would suggest one most important qualification arising from the fact that the ear is a pressure-operated device, capable of assessing sound intensity at a particular point but not capable of averaging intensity over a considerable area.

It seems essential that a loud-speaker of the type described, having a constant mean spherical response, should be rendered substantially non-directional when used under normal home conditions, for the conventional position of the observer in a small room, relative to the loud-speaker, is such that he will hear a fairly high proportion of direct to reflected sound, and therefore the polar distribution of the unit is an important consideration. In this particular design, calling for a rising axial response, the listener will be apt to complain of shrillness when listening under near-axial conditions. It is felt, therefore, that some form of mechanical diffuser should be incorporated in front of the diaphragm, or the unit should be so placed in the room that the observer must be well off the axis at all times. These precautions are not necessary with the average loud-speaker, where axial response is held approximately constant. It is true that there is a lack of "top" off the axis, but this is, as it were, a negative effect, and does not cause discomfort to the ear.

(B) *Variation of axial and mean spherical response with frequency.*

It is agreed that a definite relation can be established between axial and mean spherical response, for a given loud-speaker. The authors state that for constant mean spherical response an axial curve rising a given number of decibels per octave is required over the frequency range covered by this loud-speaker. As we understand it, the difference between axial and mean spherical response is a function of the focusing effect of the diaphragm, where its diameter becomes comparable with the wavelength of sound reproduced. In this event a practical case should show a decreasing difference between the two responses below, say, 500 c./s. A study of Figs. 1 and 2 would seem to bear out this hypothesis. In Fig. 1, axial and mean spherical responses are seen to coincide closely from 100 to 500 c./s., while the plotted points of Fig. 2 also indicate that the ratio of axial to mean spherical sensitivity can be regarded as constant over this range. The result, then, of designing the loud-speaker to have a steadily rising axial response of 2.5 db. per octave would seem to be the introduction of a progressive bass loss below 500 c./s.

(C) *Frequency response of curved diaphragms.*

With regard to the response variations possible when using various types of moulded paper cone, we would point out that 8-in. diameter curvilinear diaphragms have been developed for commercial use, having a response maintained up to 8 000 c./s., with a maximum

deviation of ± 2.5 db., the general slope being dependent upon the ratio of diaphragm to speech-coil mass, and the variation of speech-coil current with frequency. (In this connection it would be interesting to know the exact method of feeding the speech coil in the authors' investigation, as this obviously has a profound effect on the responses obtained.)

As the diameter of the curved diaphragm is reduced below 8 in., however, the response becomes increasingly peaky, and we have not yet succeeded in developing a sample that can be regarded as satisfactory from all points of view. This lines up with the authors' findings.

(D) Other factors.

The efficiency of the unit will be less than that of the average quality speaker, both as a result of enclosing the back and specifying a flux density of 6 000 lines per cm^2 , which we regard as rather low. The fact that the speech coil is only 10 % longer than the gap will tend to limit undistorted output severely, and it is felt that harmonic distortion in the bass, together with attendant intermodulation, will be noticeable at moderate output levels.

In the light of practical experience we forecast that quantity production will be somewhat hazardous and expensive, in view of the method of cone suspension and the small speech-coil clearances allowed.

Finally, we notice that the speech-coil lead-off wires are a continuation of the winding. This small-diameter solid wire will be somewhat liable to breakage due to continual flexure while in use, therefore we would recommend that the leads from the coil be run a short distance up the cone and eyeleted thereto. The lead-off wires can then be of the conventional copper-tinsel type.

Messrs. W. West and D. McMillan (*in reply*): Mr. Cohen has drawn attention to a very important aspect of design, namely reliability in service. His remarks remind us of the considerable amount of criticism, based on manufacturing experience, which has been received and welcomed by us as helpful. Much of this criticism has not, however, been substantiated in practice. Some of the remarks in Section (D) of Messrs. Webb and Williams's contribution seem to fall into this category. We are also reminded of the lapse of time—about three years—since the investigation was carried out. At that time the axial response of the "average loud-speaker" was anything but constant; we gather from Messrs. Webb and Williams's remarks that it is now approximately constant, though this is not quite the impression we have received from such casual listening as has come within our experience.

Several contributors to the discussion have referred to the fact that the rooms we used were larger than typical living-rooms. It is, however, absorption rather than size of the room that is of importance. The conclusion that the mean-spherical response is the proper criterion to use was based fundamentally on the hypothesis that at most listening positions the reverberant sound preponderates over the direct sound. Since these two sounds cannot readily be separated, the average sound-pressure tests were made to confirm the hypothesis. These tests were made almost entirely between radii of 4 and 12 ft. from the loud-speaker, and for the most part less than 10 ft.,

to include all usual listening positions relative to the loud-speaker. Now if the surfaces of the room had been brought nearer, i.e. the room made smaller, the proportion of reverberant to direct sound could not have been decreased thereby. Consequently the general conclusion reached for the larger rooms will apply also to smaller rooms. It will not, of course, apply equally to all rooms and all individual listening positions, and if the listening position is close to the loud-speaker, on the axis, or if the room has little absorption on any of the vertical surfaces (the direction of the high-frequency beam from the loud-speaker being assumed to be horizontal), some accentuation of the high frequencies will be noticed. Room Y is a case in point, but even for this room uniformity of mean spherical sound pressure is a better criterion than that of axial sound pressure. Mr. Voigt has remarked on the unfortunate tendencies of the acoustics of some modern rooms and furniture, but loud-speaker design should not be influenced by faulty room acoustics.

Mr. Cohen, and others, have suggested the use of a diffuser to spread the high-frequency beam, and we agree that such is desirable, not only for this loud-speaker but for all that are in common use in living-rooms. This question was considered during the investigation but it was evident that an appreciable increase in cost, and probably also in bulk, would be involved; so further consideration was deferred to a later stage of development, if and when opportunity offered. Meanwhile the user has, under his control, adjustment of the direction in which the loud-speaker is oriented with respect to the usual listening positions in the room. The effect of such adjustment is not generally very noticeable.

Finding some difficulty in understanding the purport of Dr. Hughes's remarks, we shall look forward with interest to further disclosures in the publication which he forecasts. It appears that the subjective criterion which Dr. Hughes seeks to apply is that the reproduced sound in Room 2 (Fig. A) should resemble as closely as possible the original sound as heard in Room 1. This is not a criterion which can be capable of general practical application, nor is it in our view so worth while as the one we have suggested. The limitation to a "monaural" transmitting system is not an obstacle to the attainment of perfect reproduction of a single source of sound, though of course, where several sources are operating simultaneously, they must all emanate in the reproduction from a single point in the room—the loud-speaker.

Mr. King is correct in supposing that the diameter of the moving coil was chosen by us rather arbitrarily. We saw no need to go into the question of magnet design and made use of types from commercial production. The size was in very common use by manufacturers and we were therefore able to examine the performance of a large number and variety of samples of cones on the same experimental mounting. Perhaps the most interesting feature of the large coil design which Mr. King has described lies in his suggestion that response over a wider range of frequencies can thereby be obtained from the cone. Messrs. Webb and Williams regard 6 000 lines per cm^2 as being rather low, but this figure was quoted as the minimum value for specification purposes; since sufficient sensitivity for the purpose required could be obtained therefrom, there was no point in making the

specification more severe, though it was stated that sensitivity would be one of the factors to be considered in the placing of any contract resulting from the submission of contractors' samples. The statement that enclosing the back of the loud-speaker reduces its efficiency needs some qualification, as it has been demonstrated that over a useful range of low frequencies it has the reverse effect.

Flight-Lieut. Scroggie prefers the method of comparison in which the listener moves between studio and listening room, to the one in which the source of sound is transferred. For some purposes, such as the placing of microphones or arrangement of studio for particular items, the method he prefers is the best, if not the only practicable one; but for the design of a loud-speaker it involves the sacrifice of a tangible standard. Flight-Lieut. Scroggie's objection to the standard which we suggest lies in the necessary restriction (for the design of a loud-speaker) to sources of sound which could by nature be heard in the listening room. He offers no alternative meaning to the phrase "faithful reproduction," which is generally recognized as the desirable objective of design but which will never be attained unless it has a definite and real significance. We do not think that aesthetic considerations should enter into the design for performance of a loud-speaker; they are proper to the production of the sounds, to adjustments of the acoustics of the rooms and to locating microphones for individual programme items, but not to the transmitting or reproducing system. They are not allowed to enter into the design of microphones or amplifiers and there is no justification for making an exception in the case of loud-speakers. Nothing is really lost by restricting comparison (for assessing performance of the system) to individual sources of sound; there is a sufficiently wide variety readily available and the basis of comparison is unequivocal. With a system that is near to perfection on this basis and with a studio technique based on a comparison of the kind that Flight-Lieut. Scroggie advocates, using a "typical" listening room for monitoring, the best results possible for the listening room concerned will have been achieved.

Perhaps the interpretation of "faithful reproduction" which we are using can help to answer Mr. Voigt's question about the preferred position of a loud-speaker. For individual sources of sound, e.g. the speaking voice, it is required that the reproduction shall sound as though the original source were in the room. To assist the illusion it is clearly helpful that the sound should come from a point in the room which could naturally be occupied by the originating source. From this aspect there certainly is objection to allowing the sound to come from the floor.

We agree with Flight-Lieut. Scroggie that frequency distortion is by no means the only factor to consider in the performance of a loud-speaker; it was, however, the outstanding weakness of ordinary design, and our attempts to eliminate this weakness are the justification, or excuse, for this paper. Other factors were not ignored by us, but further possibilities of improvement were relegated to consideration at a later stage of development, when time had permitted a proper sense of proportion to be acquired of the various possible imperfections remaining in the performance of the manufactured product.

We regret that circumstances have so far prevented further work by us on this problem. The generation by the loud-speaker of inharmonic tones, or "buzz," certainly deserves serious attention; the spider is perhaps the usual cause of the most noticeable manifestations. We did not attempt at this stage to specify particular means for avoiding this trouble, since many manufacturers' products are reasonably free from it. Mr. Voigt mentions damping pads; if these are effective in practice the idea is sound, so also is a reduction in mass of the parts of the spider which can vibrate in unwanted modes of vibration. In our design a contribution of stiffness by the spider is not required and a very light construction should therefore be possible. The desirability of avoiding tension was mentioned in the paper.

It is not likely that the suggestion to select test angles giving equal divisions of space for calculating mean spherical sound pressure would give a better average than testing at equal angles—for the same number of test points. At the lower frequencies the readings at 30° and 60° are almost as large as those on the axis, while at the higher frequencies the influence of tests at other angles is small. If angles giving equal divisions of space were used, less data would be obtained of the concentrating of the beam at the higher frequencies, since the nearest test angle to the one on the axis would be much greater than 30°.

We received no ready-made samples of the double-cone type of diaphragm mentioned by Flight-Lieut. Scroggie, and we did not, in the present stage of development, initiate any experiments with this type of construction because of the greater cost likely to be involved. We were rather doubtful whether a mechanically coupled radiating system of this kind could be made to produce so smooth a frequency-characteristic as has been obtained from a simple diaphragm.

In reply to Mr. Turner's question on price, it can reasonably be stated that the quotations we mentioned compared favourably with prices for loud-speakers supplied to relay companies. We see no great objection to fitting a loud-speaker in the same cabinet as a radio receiver, if it is done without sacrificing the performance of either. The loud-speaker would require a separate division in the cabinet if it has an enclosing case—as we advocate—since it is undesirable from the points of view of maintenance and heat dissipation to enclose the radio receiver.

The "2½ db. per octave" rule is purely empirical and, as Mr. Voigt correctly states, is intended only as an approximation. It is used as a convenient guide to the main objective, namely a uniform frequency characteristic of mean spherical radiation. We also expected at low frequencies the decrease of slope, asymptotic to the horizontal, to which Mr. Voigt refers, but we did not consider that the results of Fig. 2 justified the complexity involved in altering slightly the simple rule, in the present state of the art of controlling the frequency characteristics of loud-speakers. Messrs. Webb and Williams have also raised this question but we think that they have exaggerated the difference to be expected. At 500 c./s., and even at considerably lower frequencies, the distribution of radiation has become markedly distorted from the

spherical shape. It is not only the size of the cone, but also the size of the loud-speaker, relative to a wavelength, that contributes to the effect.

As Mr. Voigt has supposed, triode amplification was

Table A

Frequency	Impedance	Angle	Frequency	Impedance	Angle
c./s. 70	ohms 3.3	—	c./s. 400	ohms 2.4	+ 7°
100	3.2	— 12°	600	2.6	+ 20°
120	2.7	— 13°	1 000	3.1	+ 31°
150	2.4	— 6°	2 000	4.4	+ 42°
200	2.3	0	5 000	7.4	+ 50°
300	2.4	+ 10°	7 000	9.3	+ 52°

used in the power stage feeding the loud-speaker; the investigation did not include experiments with different types of amplifier or circuit connecting the loud-speaker. Table A shows the impedance variations of a loud-speaker made to the specification. No marked irregularities

were noticed at frequencies intermediate between those stated.

The resonance at 30 c./s. (mentioned in Section 5.2) relates to the loud-speaker unit only; when the unit is assembled in the case, the resonance frequency is raised to somewhat over 100 c./s.—for the particular size of case specified. This accounts for the diminishing output at lower frequencies.

The answer to the question on moths is simply that, with a gauze cover over the aperture in the front of the case, access for moths is prevented.

We regret that we are not now in a position to give Mr. Voigt further information with regard to the very exceptional cases of large errors in the average of 9 readings, mentioned in Section (2.2). These errors are somewhat greater than can be expected with a normal error distribution, and it is possible that the results may have been influenced by the causes which Mr. Voigt suggests.

We have not made direct tests of internal damping of different cone materials, but we regard it as a helpful factor for obtaining a smooth frequency characteristic.* The mechanical tests mentioned in Section (4.6) can perhaps be regarded as confirmatory, since increased internal damping can be expected with a weaker moulding of the paper, the small fibres being less firmly bonded together.

* See W. WEST: "Acoustical Engineering," pp. 166 and 167 (London, 1932).

METER AND INSTRUMENT SECTION: CHAIRMAN'S ADDRESS

By F. E. J. OCKENDEN, Member.*

(Address received 4th April, 1940.)

The change in circumstances which has made it impossible for me to give you my Address in person is one which we all regret. I cannot now express, in the manner to which I had looked forward, my very great appreciation of the honour conferred upon me by my election to the Chair for the present Session.

This Section of The Institution owes much to a succession of able chairmen, and my doubts concerning my ability to carry on the high standard which they have established are accentuated by a foreboding that the war conditions under which we now labour will add very greatly to the difficulties involved in maintaining the activities of the Section at a level even remotely approaching that to which we all looked forward so confidently in the spring of 1939. Nevertheless, it will be my endeavour to promote the interests of the Section to the utmost and I hope that my successor may come to his term of office under happier conditions.

The subject which I have chosen for the technical portion of my Address is a general survey of the many optical devices which are used by, or are of interest to, the meter and measuring instrument engineer. I do not suggest that the items which I propose to discuss are in any way original or that descriptions of them are not to be found elsewhere. Often, however, the optical training of the electrical engineer consists solely of such portions of the lectures covering "Light" as he contrives to absorb during his early student days, so that a brief outline of the principles involved in the more common optical appliances, together with a description of such as are of an unusual nature, may possibly form a useful source of information for those whose theoretical knowledge of such matters has grown somewhat "rusty."

Probably the earliest application of an optical device to an electrical measuring instrument was that embodied by the late Lord Kelvin in his mirror galvanometer which he patented in 1858. According to the late Silvanus Thompson, the idea of using a beam of light as a weightless pointer was the happy result of a casual observation of the light reflected from a monocle which, being short-sighted, Lord Kelvin habitually carried. The use of his instrument contributed very largely to the successful working of the Atlantic cable, and although for many years the use of the mirror was confined to galvanometers there has been a marked tendency of late to use the deflection of a light spot quantitatively against a calibrated scale, and many deflectional instruments (some even of a portable pattern) are now so constructed. For this class of instrument it is desirable to project on to the reading scale a clear and evenly illuminated disc of light, across which must appear an image of the index line sufficiently clearly defined to

permit of accurate readings being taken, even on a finely divided scale. Since the ratio of mirror diameter to focal length is usually so small as to make spherical aberrations quite imperceptible, the sharpness of this image depends only upon correct focusing and the accuracy to which the mirror is ground. Unless, however, the disc from which the mirror is made is fairly thick, the flimsy nature of the average concave mirror does not permit of highly accurate grinding, and for many purposes a thin plano-convex lens (having its plane face silvered) produces altogether superior definition. Not only has this the further advantage that it does not suffer from the astigmatism which is inherent in a spherical reflector (used otherwise than at an angle strictly normal to its face), but the absence of double reflections permits the adoption of the more usual, and more highly reflective, back silvering, instead of the surface aluminizing which is both easily damaged and of considerably lower reflective value. The maximum diameter and evenness of illumination of the light disc, on the other hand, are controlled by the quality of the "lantern" lens or condenser fitted to the lamp. The double spherical lens usually employed is quite inadequate for the projection of a satisfactory disc, as the spherical aberrations of this form of lens are very great and only very low apertures (i.e. ratio of diameter to focal length) can be employed with success. Fig. 1 shows the relative spherical aberrations of various forms of simple lenses by giving the ratio between the foci of the outermost and central rays for lenses of similar focus and diameter, and therefore of the same light-gathering power. It will be seen that the double spherical lens (a) mentioned above has the largest aberration: a plano-convex lens (b) of the same focus is somewhat better, and a combination of two thin plano-convex lenses (c) or (d) of the same effective focus is an improvement on any single lens. Of these (d) is probably the best possible for an inexpensive unit. It is of the utmost importance that in all cases the plane side of the lens be turned in the direction of the focus of greatest obliquity, usually towards the lamp.

When the length of the deflecting beam is very large (of the order of 10 ft. or more) the use of achromatic lenses for the lantern is more than justified since the superior chromatic corrections of such a lens will enable it to project a disc having an even brightness quite unattainable with even the most carefully adjusted of simple lens combinations. Fig. 2 (see Plate 1, facing page 456) shows an electrostatic voltmeter intended for use up to 300 kV and fitted with achromatic lenses. Excellent definition is obtained in spite of the fact that the deflection is read on a scale mounted on a control panel nearly 12 ft. away from the actual instrument. Remote control, by means of small a.c. motors, enables

* Messrs. Everett, Edgumbe and Co., Ltd.

the voltage range to be altered by suitably separating the voltmeter electrodes, and a duplicate optical system, attached to the bar carrying the movable electrodes, enables the range for which the instrument is set to be read directly on a second scale mounted in the same frame as that indicating the voltage.

An interesting variation of the deflectional light-spot arrangement is shown in Fig. 3, whereby the serious

earlier, that the plane side of a plano-convex lens should face the side of shortest focus, i.e. of greatest obliquity. The objective, on the other hand, works under conditions involving considerable magnification, the focus on the screen side being some 10 times the focus on the scale side, and an arrangement similar to that shown in (c) (Fig. 1) is preferable, the plane side of both components being towards the scale. This arrangement is more

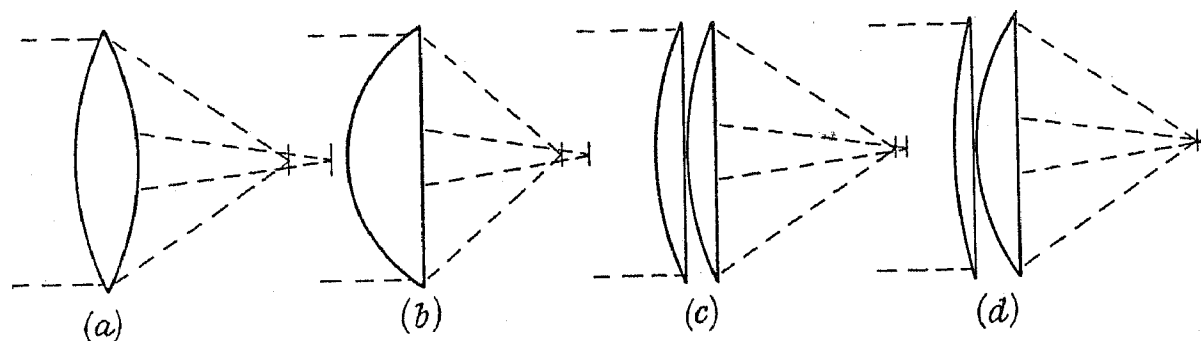


Fig. 1

(a) Error 17.3%.
(b) Error 12.1%.

(c) Error 4.3%.
(d) Error 3.9%.

difficulties which arise due to astigmatism when the angle between the incident and reflected beams on the mirror is very large are obviated. In this instrument the scale, which has a total angular value of 200 degrees, is split up into three sections, each of 70 degrees. These are mounted horizontally one over the other, and a similar number of "spotlights" are so disposed on the instrument base that, as the mirror M attached to the instrument spindle rotates, the beams from the lamps are brought successively to the starting end of the appropriate scales, the spot appearing on Scale 2, for example, just before the spot due to the preceding lamp leaves Scale 1. The slight overlap provided ensures continuity of reading and facilitates the adjustment of the lamps to their correct relative positions.

An alternative method of projecting the reading of a deflectional instrument is shown diagrammatically in Fig. 4. In this device the scale S, printed upon thin transparent celluloid, is attached to the instrument spindle in such a manner that rotation causes the scale to traverse the optic axis of a simple projection system. The particular portion of the scale which is in the axis when the instrument comes to rest is thus projected as a "picture" on to a translucent screen G mounted at the front of the instrument case. Since the magnification is about 10/1, the accuracy of reading is very high—a scale $2\frac{1}{2}$ in. long having an effective length on the screen of about 2 ft., only a limited portion being visible at any one time. The optical system consists of two units, a "lantern" condenser, C (comprising two plano-convex lenses mounted with their convex faces inwards), and a projector lens or objective O. The condenser provides the objective with a "Maxwellian view" of the light source L, thus ensuring that the whole of the projected picture is evenly illuminated. The distance LC is substantially the same as the distance CO, the foci on either side of the lens being alike and fairly short. The light in the centre of the condenser, on the other hand, is approximately parallel, so that this arrangement complies with the condition laid down

satisfactory than the usual one shown at (a) in Fig. 4 and enables either sharper definition to be obtained for a given aperture or a larger aperture (and therefore a more brilliantly lit screen) to be utilized for the same degree of definition. Fig. 5 (Plate 1) shows a view of the complete instrument as used for temperature indication. This arrangement has much to recommend it, since a clear indication of the reading is obtainable from even the

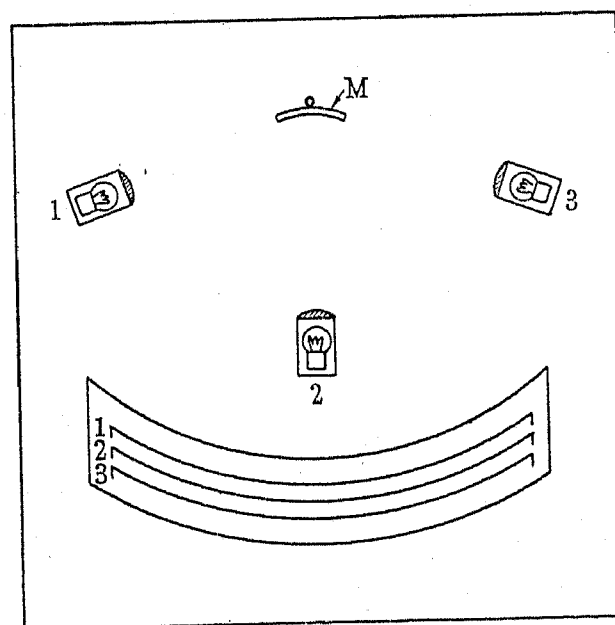


Fig. 3

most casual glance at the instrument face, but the amount of light available to illuminate the comparatively large "picture" is limited by the small aperture possible with a simple optical system. Where circumstances justify the extra expense, an achromatic objective of larger aperture is to be preferred.

Although the instrument just described is suitable for many purposes, it suffers from the disadvantage that the scale used has appreciable weight and is mounted at some distance from the axis of revolution of the movement, thus adding considerably to the moment of inertia of the

system to which it is attached. It is therefore unsuitable for application to sensitive galvanometers or other devices where low momentum is important. An arrangement due to Pattee (U.S.A.), in which two mirrors are used in conjunction with a fixed radial scale, obviates this difficulty and produces a moving image of the scale on a fixed

lines remain fixed, their position being determined solely by the position of the lamp and objective, and these can thus be adjusted with great accuracy. The scale is polished in order to reflect as much light as possible through O, the marking being reproduced on it photographically.

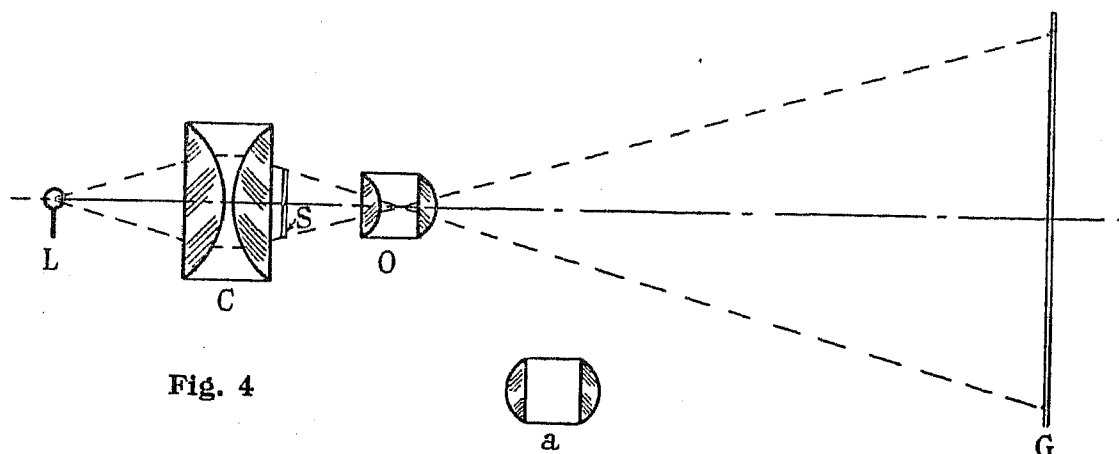


Fig. 4

screen, without at the same time adding anything to the weight of the movement other than that due to a light axially-mounted mirror. The layout is shown in Fig. 6, where L is the lamp-housing carrying a lantern lens A. B is a concave mirror, attached to the instrument spindle and focusing an image of A at any point P on the highly polished cylindrical scale S, P being that point on the scale which the movement "faces" and which it is thus

In many cases where a reflected beam is used as an indicator of an instrument deflection, a second mirror may conveniently be employed in order to shorten the length of the containing box without sacrificing the sensitivity obtainable with a long beam. It has been pointed out by more than one writer that if the second mirror is cylindrical in form, a second stage of amplification of the angular deflection is obtained, since a small change in the

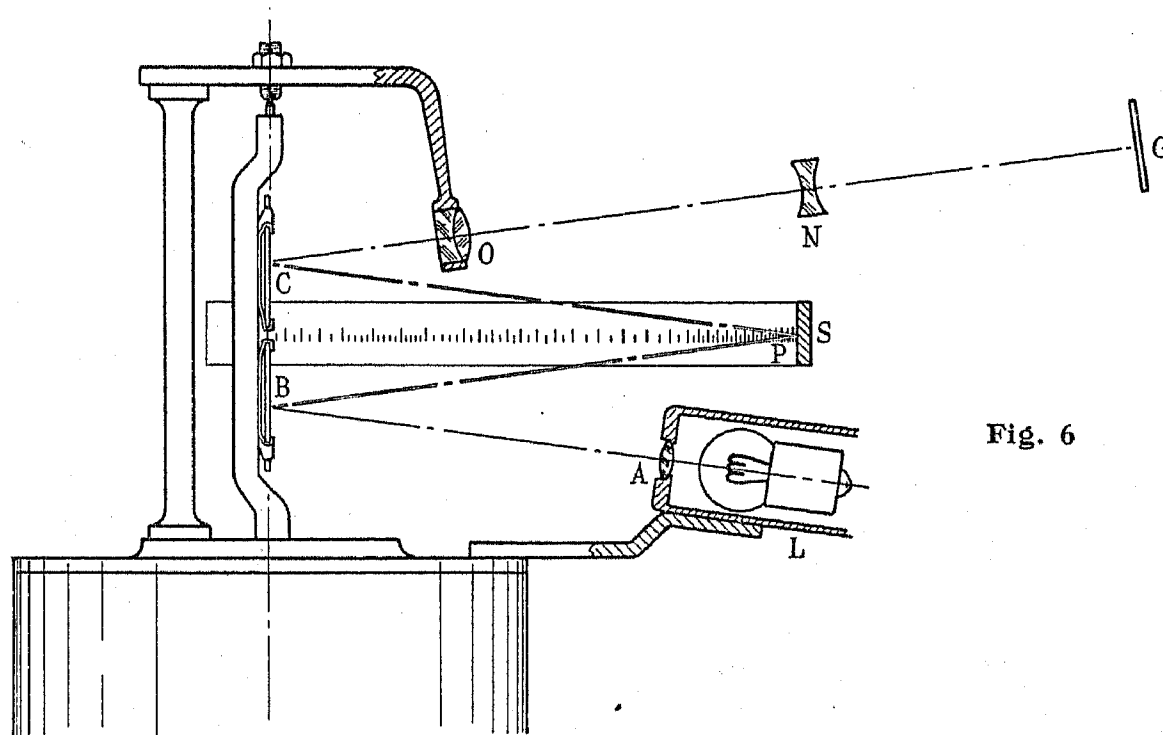


Fig. 6

desired to project on to the instrument screen. C is a plane mirror throwing the beam (reflected from S at the point P) through an achromatic objective O on to the screen G. A concave lens N is used as an eyepiece or projector lens as in the case of the Galilean or "Telephoto" system, and enables a greatly enlarged image of P to be thrown on G without the use of a long beam. It will be seen that in this system the only rotating optical units are the two mirrors and that only the two beams shown by thin double lines actually swing round the axis of the instrument. The other two beams shown as single

position of the beam incident on the cylindrical surface causes a much greater change in the angle of the reflected beam. The arrangement usually proposed is shown in Fig. 7, where L is the lamp, M the spherical galvanometer mirror rotating on axis A, and C the cylindrical reflector. It will be seen that a change α in the position of the beam from the full to the dotted line results in a change in the angle of the reflected beam of β , where β may be, say, 10 times α . It must be pointed out, however, that since the width of the image of the index line subtends a small but definite angle, this angle is also increased by some

10 times when the beam moves to the dotted position, causing the width of the line to be increased by a corresponding amount, and the accuracy of the reading so attainable is thus no greater than would be obtained with a critically sharp image of the line travelling over a finely divided scale. This example serves to emphasize a feature of optical projection which is but rarely sufficiently appreciated, i.e. the value of the projection device as a means of amplifying the sensitivity of an instrument is largely controlled by the degree of perfection of the definition obtainable, and this is dependent both on careful design and upon the employment of the best-quality optical units.

An excellent example of the value attached to even small gains made in this way is to be found in the design

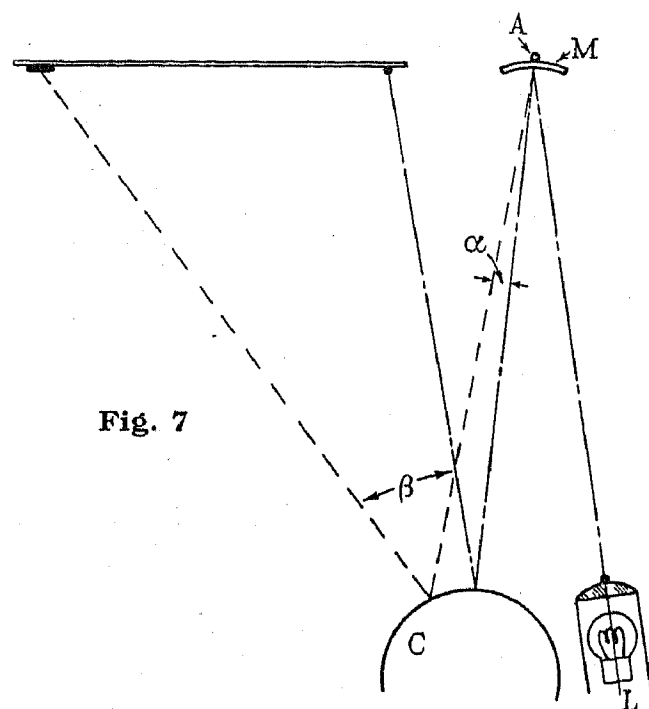


Fig. 7

of the optical system of the Duddell oscillograph. The usual arrangement is well known but is shown for convenience in Fig. 8, where L is the lamp or light source, C the condenser, and F a fine slit cut in an opaque diaphragm mounted in front of C. A plano-convex lens O, in conjunction with the vibrating oscillograph mirror M, focuses an image of the slit on to the surface of the photographic recording drum, H. By interposing between M and H a cylindrical lens D having a length equal to the length of the drum, the image of the slit is reduced to a small spot, no matter at what point the image may happen to strike the drum. The smallness of the spot, and therefore the fineness of the trace forming the record, is dependent on the accuracy of adjustment and the quality of the units used.

In general, the dimensions of the slit and the mirror are so small compared with the length of the beam that the corrections of the lenses used are of little importance. Where, however, as is sometimes the case, two pairs of oscillograph "strings" with their associated mirrors are mounted in a common oil bath behind a single lens, the mirrors have to be mounted symmetrically some little distance from either side of the lens centre. In this case an achromatic combination for O has been found to be preferable, since it eliminates the slight chromatic blurring of the spots resulting from the prismatic action of the two sides of an uncorrected lens. Until recently, it

was also usual to make the cylindrical unit of a single component with all the chromatic errors inherent in an uncorrected lens of great curvature. A recent improvement embodies an achromatic cylindrical combination and this has improved yet further the critical definition which is a characteristic of electromagnetic oscillographs and which is indeed their chief point of superiority over cathode-ray indicators when used for power frequencies. The high-quality definition obtained with these instruments is excellently shown in the 6-element oscillogram reproduced in Fig. 9 (Plate 2).

The apparently simple operation of reading the pointer deflection on a substandard instrument is complicated by the fact that, since the pointer and the scale cannot conveniently be made to occupy the same physical plane, parallax effects are liable to mar the accuracy of the readings, particularly if a precision of 2 or 3 parts in 10 000 is aimed at. The use of a mirror underneath the pointer as an anti-parallax device is well known, but its use for a prolonged period involves considerable eye-strain, and unless the tip of the pointer is exceedingly

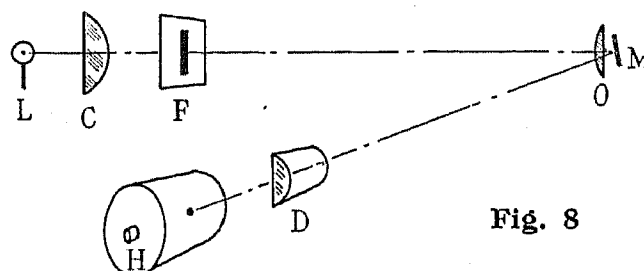


Fig. 8

thin an error in parallax which is imperceptible in the mirror may, nevertheless, introduce an appreciable discrepancy into the readings.

It has been pointed out by Edgcumbe that the strain on the eye is materially reduced if the edge of the scale and the edge of the mirror are contiguous. Fig. 10 (Plate 2) shows a scale and mirror arranged in this manner: it shows also the value of a magnifier mounted co-axially with the pointer staff so that it may readily be swung to follow the movement of the pointer. The lenses of the magnifier shown are arranged as in (c) (Fig. 1), and the small amount of distortion introduced, compared with the magnification obtained by this arrangement, may be judged from the photograph. The closeness of the scale to the mirror edge reduces to a minimum the shift of viewpoint required to transfer the eye from parallax checking to the actual observation of the pointer reading.

It would appear that this method of increasing the accuracy of reading has some advantages over the use of the so-called "vernier" scale, particularly when the error introduced by the smallest deviation of the pointer tip from the strictly radial is considered.

Another arrangement, due to Forester, also employs a mirror, but this, instead of being mounted underneath the pointer in the usual manner, is placed underneath the scale, the latter being drawn and fixed with its "back" to the observer, who sees the reflection of the scale as far apparently behind the mirror as the scale is actually in front of it. The pointer tip is caused to move in the plane of the reflected image, with which it can be made absolutely coincident. The arrangement is shown in Fig. 11, where S is the scale, M the mirror, and R the reflected image as seen in the mirror when observed, from

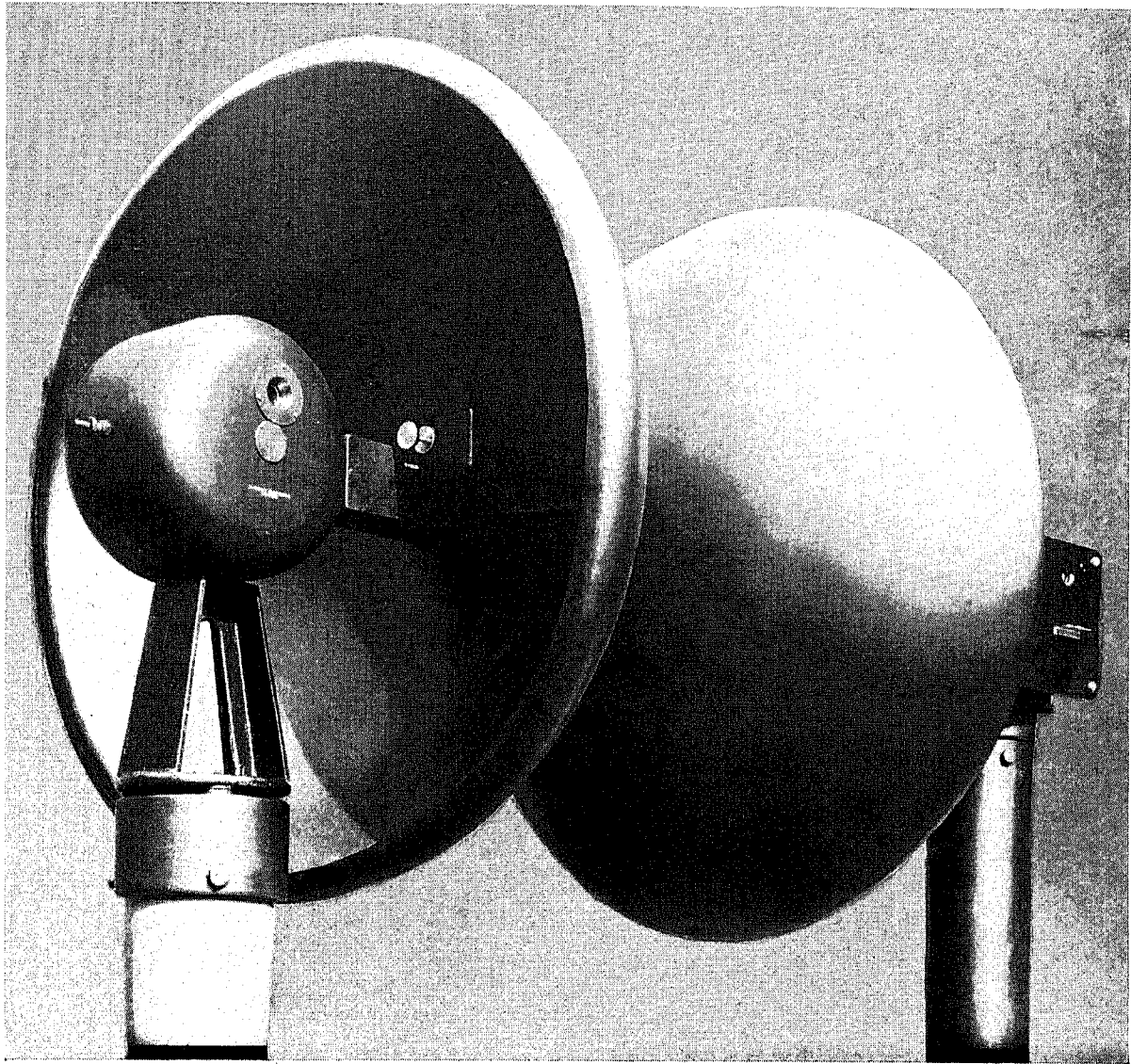


Fig. 2 (approx. $\frac{1}{3}$ full size).

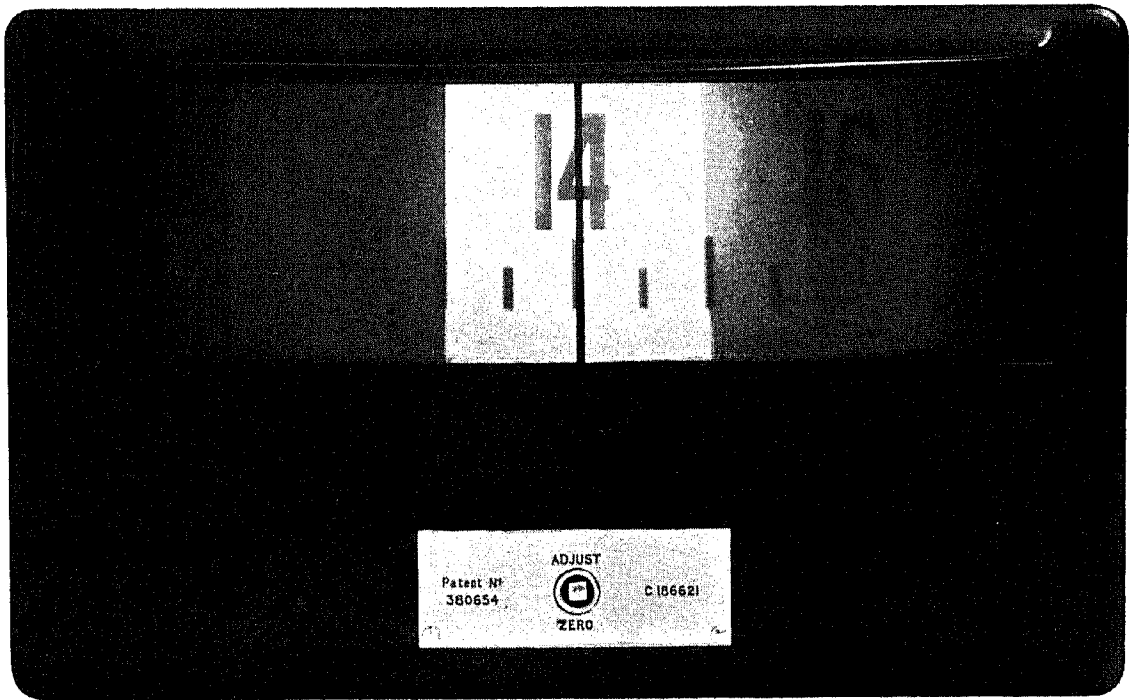


Fig. 5

Plate 2

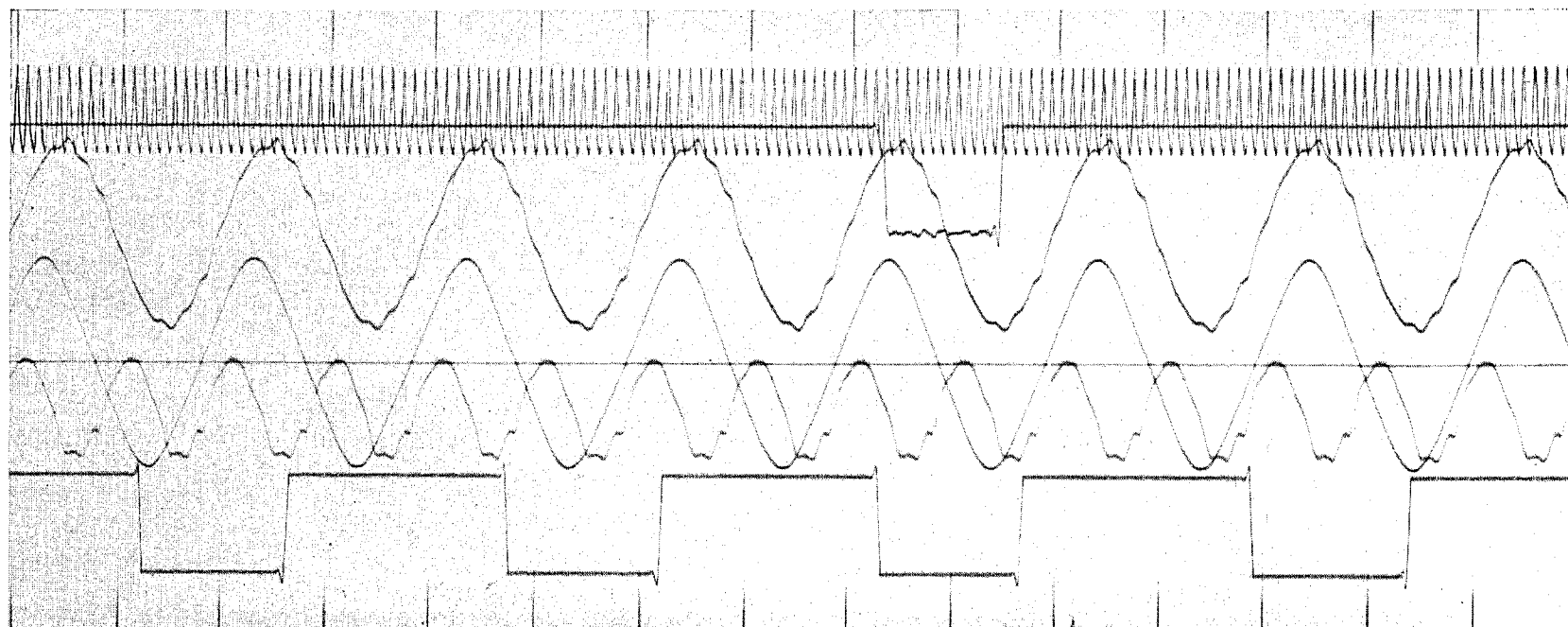


Fig. 9

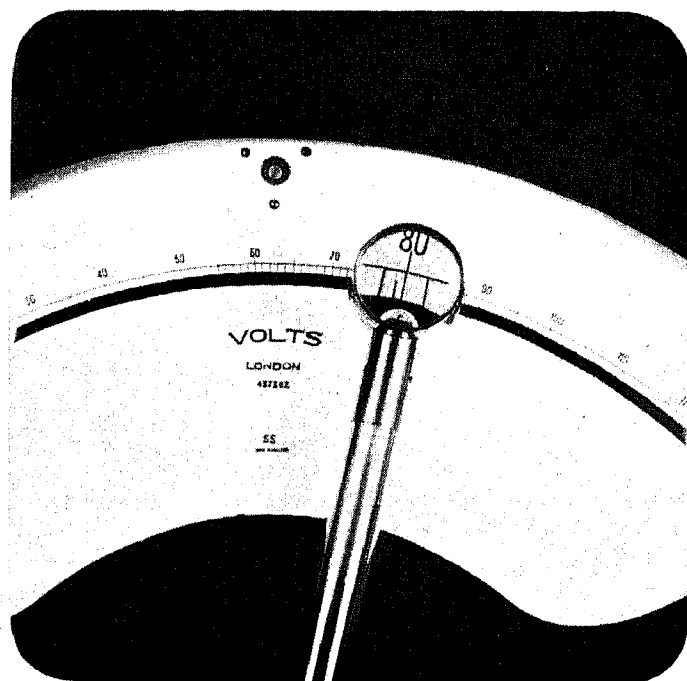


Fig. 10

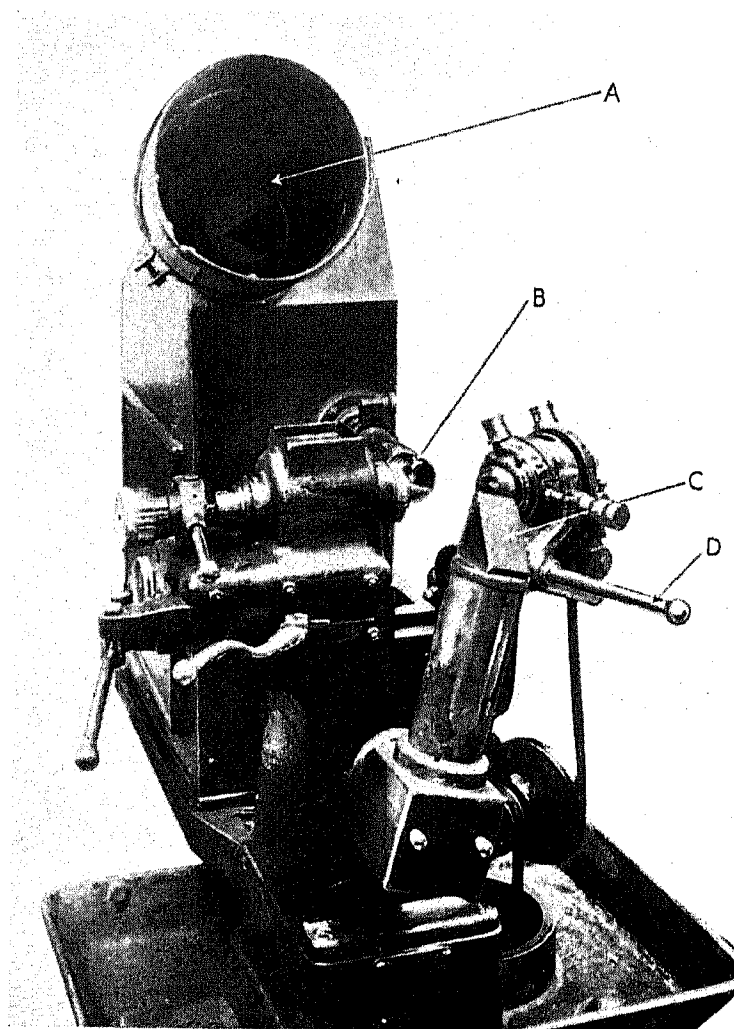


Fig. 13

above, in the slightly slanting direction shown by the arrow. To avoid obstruction of the view of the pointer tip by the thickness of the mirror, the latter must either be exceedingly thin or surface-silvered and chamfered off at the back in the manner shown. It will be appreciated that, since with this construction the pointer is in the same optical plane as the scale reflection, a magnifier or reading telescope can readily be used to increase the precision of reading, with the added advantage that, no matter how high the magnification, both pointer and scale may be focused simultaneously.

The small size of many instrument and meter parts, together with the high degree of manufacturing accuracy required, if rapid and satisfactory production is to be maintained, calls for the employment of inspection devices incorporating some degree of magnification. This is particularly the case where the inspection of pivots

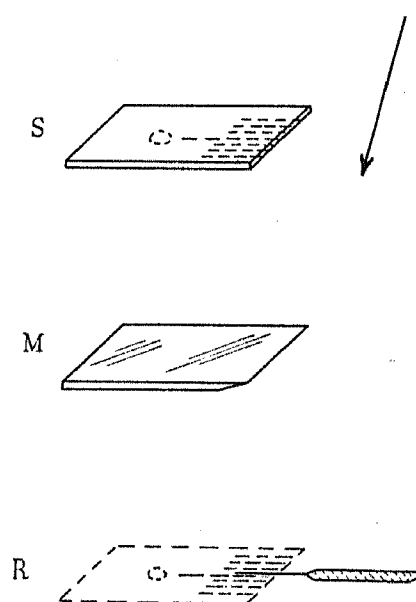


Fig. 11

and jewels is concerned. Whether the actual inspection is carried out directly or by projection on to a separate screen, the construction usually embodies some variation of the so-called "compound microscope," and a brief consideration of the optical design may be of assistance when choosing an instrument for any given purpose.

The essential parts are shown in Fig. 12, where C is the sub-stage condenser, and O the objective furnishing the primary magnification of the object X and projecting an image of X on to the plane G, where it is further magnified by the eyepiece E. Where the object to be examined is both opaque and so large that no light can be transmitted round it, the condenser is valueless and use must be made of some form of powerful top light or vertical illumination, but such conditions are unusual. The function of the condenser is not, as is often imagined, to "increase" the light by concentration, but to provide the objective with a cone of light equal to the latter's angular aperture, thus permitting the whole of the light-gathering and resolving power of the objective to be utilized. By "resolving power" is meant capacity to separate fine detail, a quality which is, for a lens of otherwise first-class construction, directly proportional to the aperture.

The standard aimed at for general microscopical work

is usually much higher than can be utilized for ordinary engineering inspection, and, since large aperture is only obtained by sacrifice of working distance (i.e. the distance between the lens and the object examined), lenses of low

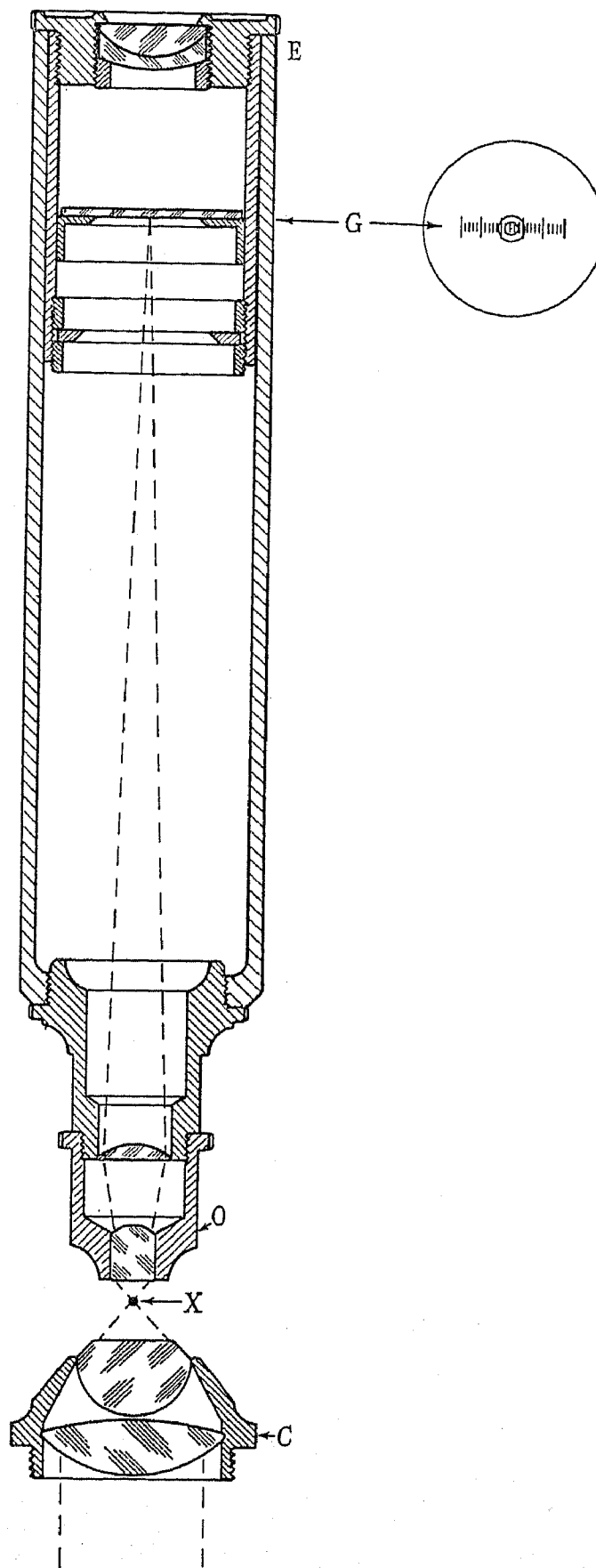


Fig. 12

aperture and large working distance are generally considered to be preferable. Excellent single lenses of modest aperture, giving initial magnifications of from 7 to 15 times, are available, the working distance in the case of the former being as much as $1\frac{1}{2}$ in. and for the latter well over $\frac{1}{2}$ in., and such distances are sufficient readily to permit the handling of small parts beneath the lens

without inconvenience due to the proximity of the lens front.

The purpose of the eyepiece is to magnify yet further and, where required, to project the original image produced by the objective. Eyepieces are of two patterns, the negative or Huyghenian and the positive or Ramsden, and the useful range of magnifications is from 5 to 15 times. Of them, the negative (so called because its focal point lies within the combination) is the cheaper and is the more usually employed. It has, however, the serious disadvantage that the eye-point (that is, the distance between the lens and the eye of the observer) is very much shorter than is the case with eyepieces of the positive pattern. When, therefore, the inspection microscope is in continuous use by a single observer, the positive eyepiece is to be preferred, since the eye-strain involved whilst using it is greatly reduced and the certainty of accurate and reliable inspection correspondingly increased. Even when used for projection on to a screen, the positive type is still advantageous, since the picture produced by it (especially in the case of the higher powers) is markedly superior to that projected by a negative combination. It will be seen that the suggested range of effective magnifications covers from 35 to 225 diameters (being the multiple of the primary and eyepiece magnifications). The exact value chosen must depend on the class of work inspected. For small gears and parts of a similar nature, 35 diameters is very suitable: on the other hand, 225 diameters is not too great for the inspection of the minute pivot points used in the smallest types of indicating instrument.

An important part of any inspection microscope is the scale or other standard against which comparison of the part has to be made. This scale may be mounted in one of two positions. A very common arrangement is to project the final image on to a white screen, either of card or of ground glass, on which is drawn an outline of the requisite shape. This construction is extremely flexible, since alteration to the master outline can readily be made, but changes in the magnification, due, for example, to alteration of the distance between the eyepiece and the screen, involve changes in the calibration, and, unless such changes are carefully watched, errors in the assumed magnifying power of the instrument may easily arise. A more satisfactory design from an optical point of view is to place the mask or master pattern (in the form of a small transparency) in the eyepiece itself, coincident with the image of the object produced by the objective in the plane G (Fig. 12). This has the advantage that it is equally applicable either to visual inspection or to projection on to a screen, and indeed may be used either way as preferred. Moreover, once the transparency or graticule is mounted and the instrument set, the calibration is not affected by any chance alterations in the focusing or screen distance from the instrument, or even, in the case of the positive eyepiece shown, by changes in the power employed.

A typical construction of an optical examiner designed in such a manner as to permit work (shaping, burnishing, etc.) to be carried out on a meter pivot whilst the profile is actually visible on the screen, is shown in Fig. 13 (Plate 2). The dark pointed shadow visible in the photograph on A, the viewing screen, is the profile of the

pivot previous to burnishing. When finished, it should lie between two limits shown by curved lines. The projection lens, B, is fitted in a focusing mount and protected from damage by an external hood. A prismatic reflector, C, directs light from a lamp (contained in the base) past the pivot and into lens B. The handle D moves the rotating sapphire in a semicircular path, thus rounding the pivot point to the required contour. The whole apparatus is motor-driven and admirably adapted for the rapid and accurate production of meter pivots under commercial manufacturing conditions.

The inspection of cup jewels for electricity meters has two aspects, the checking of the radius of curvature of the jewel cup and the estimation of the degree of polish and general perfection of the bearing surface. The latter has, in the past, usually been tested by "feeling" the surface for roughness with a fine needle. In skilled hands this method has proved reasonably satisfactory, but its use is now deprecated as liable to cause damage to a previously well-polished surface, and visual inspection with a low-power binocular microscope is the method generally adopted. This form of microscope provides stereoscopic vision together with reasonable magnification, and in trained hands can be relied upon to permit of satisfactory discrimination without involving any danger to the jewel surface.

The most convenient method of checking the radius of the jewel cup is entirely optical and is as applicable to the large radii of meter jewels as to the smaller cup found at the base of V jewels used for indicating instruments. It involves the measurement of the diameter of the reflected image (formed by the polished jewel cavity) of the front of the microscope objective, O (Fig. 12), by means of a calibrated graticule, G, mounted in the focal plane of the positive eyepiece E. The approximate diameter, D , of the image obtained from a sphere or cup of radius R is given by $D = RAL/F$, where L is the optical distance between the objective and the graticule, A the angular aperture of the objective, and F its equivalent focal length. The above expression takes no account of the eyepiece magnification, the effect of which is, in the case of the positive patterns, merely to magnify both image and scale to an extent sufficient to permit accurate readings to be made. The usual method of calibration consists of measuring the diameter of the image reflected by a steel ball of known radius. The precise constant connecting D with R , so obtained, is then applicable to the checking of both convex and concave spherical surfaces, provided that the radius of the ball chosen is small compared with F . In order that the reflection of the objective front shall be readily visible, the lenses of the objective must be illuminated from the back in such a manner as to cause a clearly defined cone of light to be thrown down upon the jewel surface, without at the same time projecting upwards any light other than that reflected from the jewel. A common method of effecting this consists of interposing between the eyepiece and the objective a piece of thin glass set at 45° to the axis of the microscope. A hole inside the tube opposite the glass permits entry of light from the side; this is reflected on to and through the objective lenses. This method, however, has the disadvantage that the light also strikes the spherical reflecting surfaces of the objective itself,

causing a considerable amount of stray light to appear in the field of the eyepiece. The light fog resulting from this causes considerable loss of contrast and tends, in consequence, both to increase eye-strain and to reduce the degree of accuracy with which readings can be taken.

Fig. 14 shows an arrangement (incorporating a specially modified object glass) which has been found to give very satisfactory results and which avoids the formation of reflections likely to interfere with accurate observation. The reflector is made in the form of an annular mirror M, mounted at an angle of 45° between the lenses of an objective of 12 mm. focus and 0.34 aperture. The mirror consists of a thin silvered cover-glass having the silvering removed from an elliptical portion at the centre so that this portion appears circular when viewed down the axis of the microscope. The dimensions of the annulus so

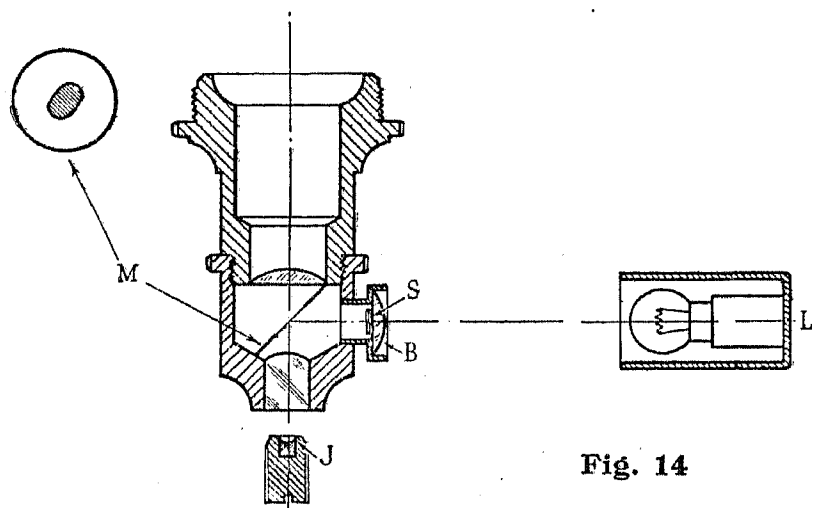


Fig. 14

formed are such that clear vision is obtainable through the inner two-thirds of the lens aperture. By means of an opening in the side of the lens mount, light from a lamp L falls upon the silvered portion of the annulus and is reflected through the front lens of the objective on to the jewel J. The image reflected thereby is projected on to the graticule through the central (unsilvered) portion of the mirror and appears as a brilliant ring, the outside diameter of which is a measure of the radius of curvature of the surface reflecting it. The lens B, mounted in the side opening, replaces, as far as the illuminating beam is concerned, the back lens of the objective and is of such curvature that the image of the illuminant is correctly in focus on the jewel surface when the image of the illuminated annulus is in focus on the graticule. A stop S, mounted on the back of B, prevents light from being reflected from the unsilvered surface of the mirror on to the back of the lens and thus causing glare to appear in the field.

By observing the circularity or otherwise of the images formed by de-focusing on either side of that point at which the reflected image appears clearly defined on the graticule, an inspection microscope of this type may also be used to detect any departure of the jewel cup from a truly spherical form.

Inspection of unmounted V jewels, with particular reference to the form and angle of the recessed cone, may conveniently be made by direct inspection through a projection microscope such as is shown in principle in Fig. 12.

In this case a small cell is mounted between the condenser and the object glass, and the jewel is examined by direct inspection whilst immersed in a suitable fluid, i.e. one having a refractive index closely approximating to that of corundum (refractive index 1.76–1.769).

Two immersion fluids are commonly used for the purpose, viz. methylene iodide (R.I. = 1.74) and α -bromonaphthalene (also known as alphabromide of naphthalene and monobromide of naphthalene) R.I. = 1.66.

The close agreement between the indices of methylene iodide and corundum makes the former very suitable for use where precision measurements are required, although its colour (a very deep orange) calls for a greater amount of illumination than would be required for a colourless fluid such as α -bromonaphthalene. The relatively low refractive index of the latter is, however, sufficient to cause appreciable distortion in the apparent shape of the cone. For example, in the case of a jewel 1.6 mm. diameter, an error of $3\frac{1}{2}^\circ$ in an 80° cone has been observed and this distortion will become progressively greater as the outside diameter of the jewel decreases. The use of this fluid, therefore, cannot be considered to be entirely satisfactory for the purpose of actual measurement; it does, however, facilitate considerably the general examination of jewels, particularly by polarized light.

It is now over 10 years since I tentatively suggested, at a meeting of this Section, that jewel examination by this means would probably be of service in determining the nature of the factors which control the durability of a jewel bearing, and I am gratified to find that in the meantime the widespread adoption of such methods of examination has added so very greatly to our knowledge of the subject. The application of this form of illumination has been greatly simplified by the introduction of so-called "polarizing filters" which consist of a film of small, accurately oriented crystals of hercynite sealed between cover-glasses. Not only are these filters less costly than the corresponding prisms which they replace, but, whereas the production of large prisms is rendered almost impossible by the absence of suitable natural crystals of Iceland spar of adequate size, the filters may be made as large as desired. For the work involved, two filters are required, one of the same diameter as the condenser C (Fig. 12) carried in a rotatable sleeve (preferably with the angle of rotation indicated on a degree scale) and mounted between the condenser and the light source, and another mounted in a cup to fit over the eyepiece E. By means of this apparatus the presence of twinning planes and other possible sources of weakness in a jewel bearing are readily detected and the angle between the optic axis of the corundum crystal from which the jewel is cut and the working face of the cup can be estimated with reasonable accuracy. Recent investigations have shown the extreme importance of these data in predicting the resistance of the jewel to deterioration under working conditions.

In conclusion, I should like to acknowledge my indebtedness to The Cambridge Instrument Co., Ltd., Messrs. Everett, Edgcumbe and Co., Ltd., Messrs. Ferranti, Ltd., and others who have not hesitated to place at my disposal descriptions and photographs of apparatus of their design with which I have dealt in this Address.

ARGENTINE CENTRE : CHAIRMAN'S ADDRESS

By W. E. TREMAIN, Member.*

"TELEVISION"

(ABSTRACT of Address delivered at BUENOS AIRES, 19th May, 1939.)

INTRODUCTION

The more one studies recent developments the more one is forced to realize that high-definition television is one of the outstanding scientific and engineering achievements of our time.

The rate of development in the last few years has been so great that it is difficult indeed to keep pace with it, especially in view of the time lag in receiving literature here.

An attempt has been made to overcome this time lag by obtaining the latest information from various sources by air mail—so that after reviewing as concisely as possible the fundamentals and certain systems of particular interest, I propose to place before you a review of the state of progress attained in the countries chiefly concerned up to the present month (May, 1939).

It is evident that it is impossible for me this evening to deal with the matter comprehensively, and in fact to attempt to do so would be equivalent to an endeavour to produce high-definition television with only 30-line transmission.

Concise description

First, we must collect data of the variations in light in the original object or scene. Secondly, we must transmit these data to the distant point. Thirdly, they must be reassembled, and fourthly, this must be done in the same sequence both as regards relative position and time, i.e. the variations must be synchronized.

At the sending end we must produce electrical variations which are a function of the light variations, and at the receiving end we must reverse this process.

An important consideration is whether in the conversion of light variations into electrical variations we shall use the incident light to *create* currents or merely to *control* them, the current being supplied by a separate source.

At present it seems that the former method has won the day.

As regards the converse at the receiving end, in spite of the astonishing success that has been attained in producing light by electronic bombardment of a fluorescent screen, I feel that the last word may not yet have been said for the control method.

Photo-Electricity

Let us then review briefly the various known means of translating light signals into electric signals.

(1) Photo-conduction.

Photo-conductive effects are well known from the original selenium cells, the internal resistance of which

decreases with an increase of incident light and can therefore be used to *control* current. But the effect is not instantaneous.

Special cells have been designed for use up to a frequency of 10 000 per second, but they are still unsuitable for the very high-frequency response demanded by high-definition television, although they were used in the early days of talking pictures.

(2) Photo-voltaic Cells.

(a) *Electrolytic*.—These consist of two electrodes in a suitable electrolyte, and develop an e.m.f. when illuminated. However, they are only of historic interest.

(b) *Voltaic-electronic cells*.—These are dry. The discovery was made in 1927, and independently in 1930, that light falling on certain solid "semi-conductors" causes electrons to leave the "semi-conductors" for an adjoining metal. Such cells are therefore self-generating or creative.

This type of cell is durable and gives relatively high output—higher even than gas-filled photo-emissive cells. Their disadvantages are comparatively low internal resistance (300 to 2 000 ohms) for use with valve amplifiers, and high electrostatic capacitance which renders them unsuitable for high frequencies.

(3) *Photo-emissive cells*.—Certain metals, especially sodium, potassium and caesium, emit free electrons instantaneously when light falls upon them.

There are two types, (a) gas-filled and (b) vacuum.

(a) *Gas-filled*.—In these a trace of inert gas is present. They give a larger current than vacuum cells, owing to "gas magnification," but as this process is attended by a time-lag this type is again unsuitable for high frequencies.

(b) *Vacuum type*.—The output of these is extremely small, but as the action is instantaneous and the capacitance is low they are the only type suitable for the extremely high frequencies involved in television.

Photo-emissive surfaces

The best results have been obtained by a complex formation of silver and caesium oxide in which caesium is embedded and over which is a layer of caesium said to be only one atom thick.

The group of graphs in Fig. 1 is a study of the spectral sensitivity of various photo-emissive surfaces. Sodium is chiefly sensitive in the ultra-violet region. The sensitivity of potassium is confined to the violet band. Rubidium is insensitive. Although the sensitivity of caesium alone is low, that of caesium oxide on silver is very high.

I venture to suggest that the expression "photo-sensitive," although frequently used, is liable to lead to

* Buenos Aires and Pacific Railway Co., Ltd.

confusion between photo-electric and photo-chemical sensitivity: I prefer "photo-emissive."

The sensitivity attained is of the order of $10 \mu\text{A}$ per lumen; the light flux on the plate of a camera from a bright outdoor picture is only about $\frac{1}{10}$ lumen, giving therefore $1 \mu\text{A}$. It must be remembered, however, that with, say, 400-line definition there are 200 000 picture elements, and therefore with 25 pictures per second each element is exposed for only $1/5\,000\,000$ of a second.

Thus the photo-electric current from a single picture element in the high lights will be 5×10^{-12} amp., and the charge resulting from this current during each scan-

Fig. 2 shows the Zworykin electron multiplier (1937), and Fig. 3 the Farnsworth a.c. type.

With these electron multipliers distortionless magnification is achieved with a low noise/signal ratio.

Cathode-Ray Tube Cameras

These were developed in different countries under such names as "Iconoscope," "Emitron," "Braun tube," etc. They are all based on the ideas of Campbell Swinton originally enunciated on the 18th June, 1908, and described with comprehensive details in his presidential address to the Röntgen Society in 1911. He foresaw

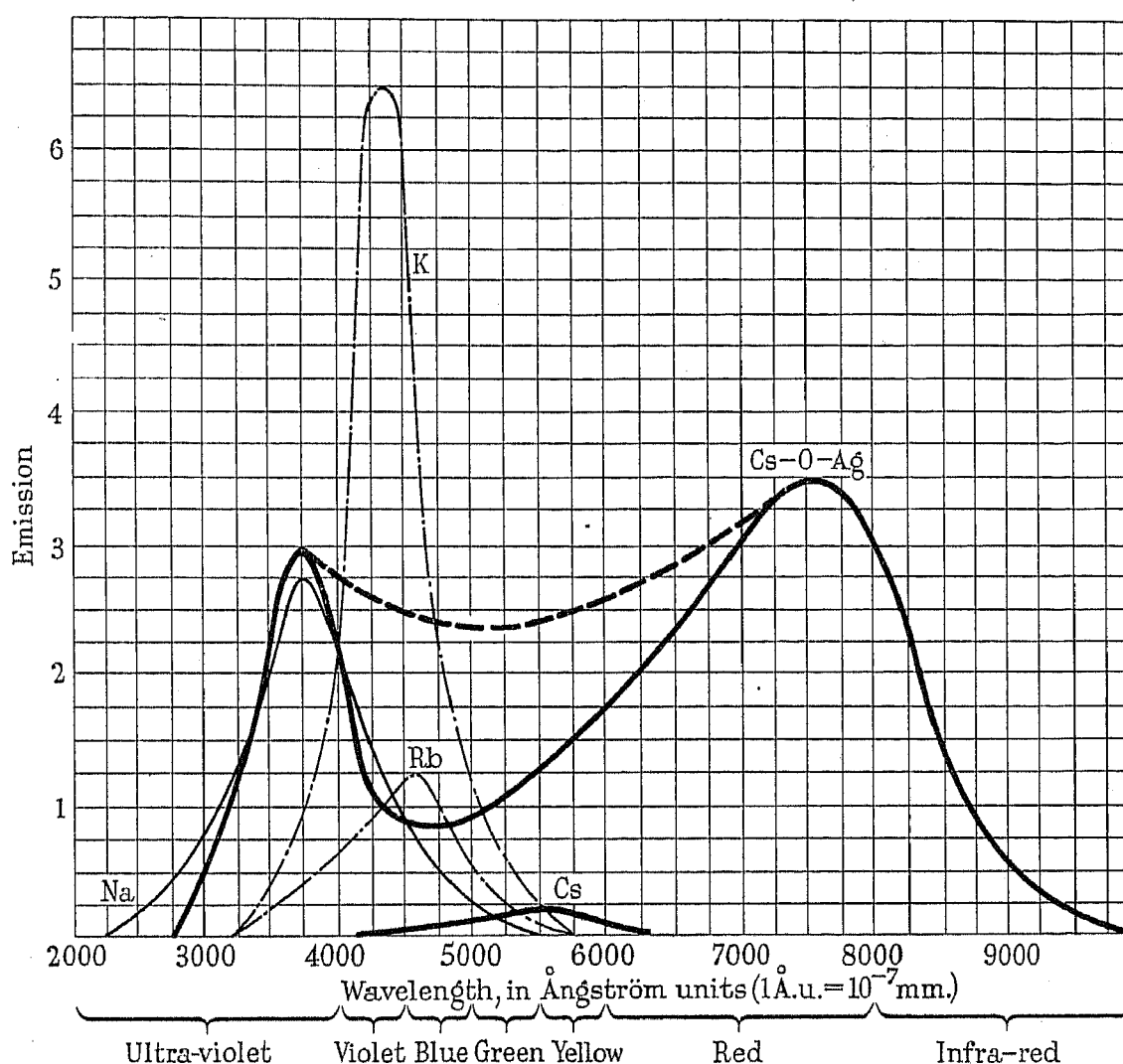


Fig. 1.—Spectral sensitivity curves of photo-emissive surfaces.

ning by mechanical scanning or any non-storage method will be 1×10^{-18} coulomb. Now the charge of 1 electron is 1.6×10^{-19} coulomb, so that it would appear that only about 6 electrons are collected from each element during each scan in the case of non-storage systems.

Electron Multipliers

Such minute quantities have to be amplified millions of times before they can serve our purpose, and to do so with thermionic valves raises the noise/signal ratio above the permissible limits. In the electron multiplier the desired result is attained by the chain-letter principle. If an electron impinges on a surface with sufficient velocity several secondary electrons are emitted from the target. With most metals there are only 2 or 3 secondaries for each incident primary, but with caesium-treated oxidized-silver surfaces the ratio is about 9 to 1.

that a great deal of experiment and much modification would be necessary to get his idea to work, and it must be remembered that in 1911 the 3-electrode valve was practically unknown and only very primitive cathode-ray tubes were available.

His scheme included scanning by controlling the cathode-ray magnetically by current from two alternating-current generators. Synchronization between the cathode-ray beams in the transmitter and receiver was provided for by deflecting coils connected by wires, and a third wire was to be used for the photo-electric vision signal currents which had to modulate the cathode-ray beam in the receiver.

Modern Television Camera

It was not until about 1932 that electrostatic focusing was introduced, but it should be clearly understood that

both focusing and scanning can be done either electrostatically or electromagnetically. The technique of focusing streams of electrons (developed under the name of electron-optics) has now been so thoroughly mastered that electron or cathode-ray microscopes have been developed.

spot corresponding to the number of picture elements concerned.

Scanning

This is performed by the application of "saw tooth"-shaped electrical impulses to the vertical and horizontal deflecting plates. These must both be linear and of course of the correct frequency, but the horizontal scan must be varied to avoid trapezium distortion due to the oblique position of the mosaic screen.

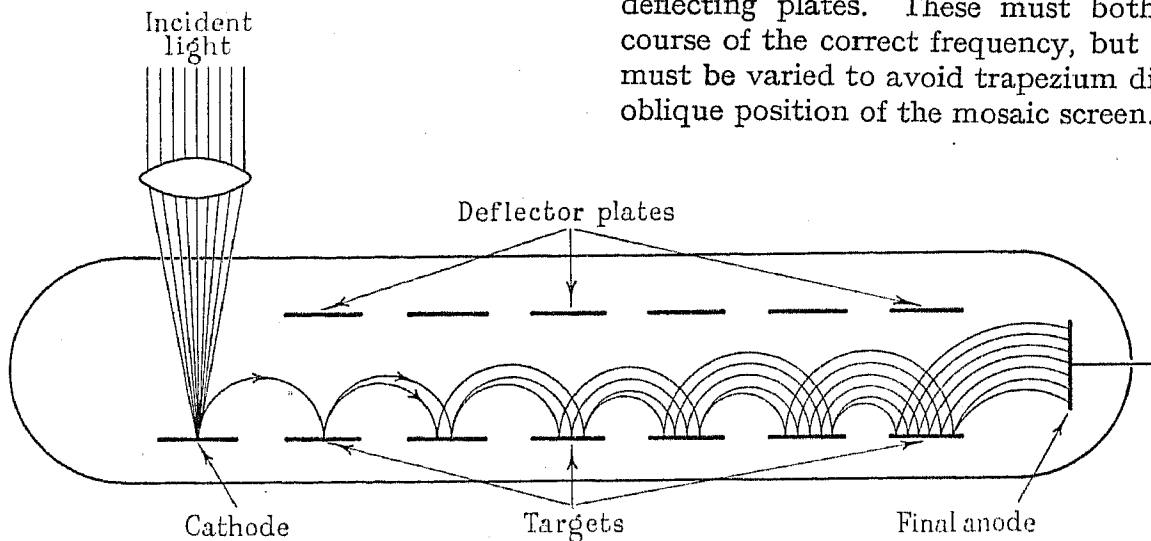


Fig. 2.—Zworykin electron multiplier, 1937.

Cathode-ray Microscope

Microscope magnification by visible light is limited by the wavelength of light to about 500 diameters (250 000 times superficially). With electron microscopes, on the other hand, magnifications of, say, 5 000 diameters are

Emitron and Super-Emitron Camera

Referring to the vision signal production, until recently the arrangement already described (based on Swinton's idea) with the optical image focused on to the mosaic

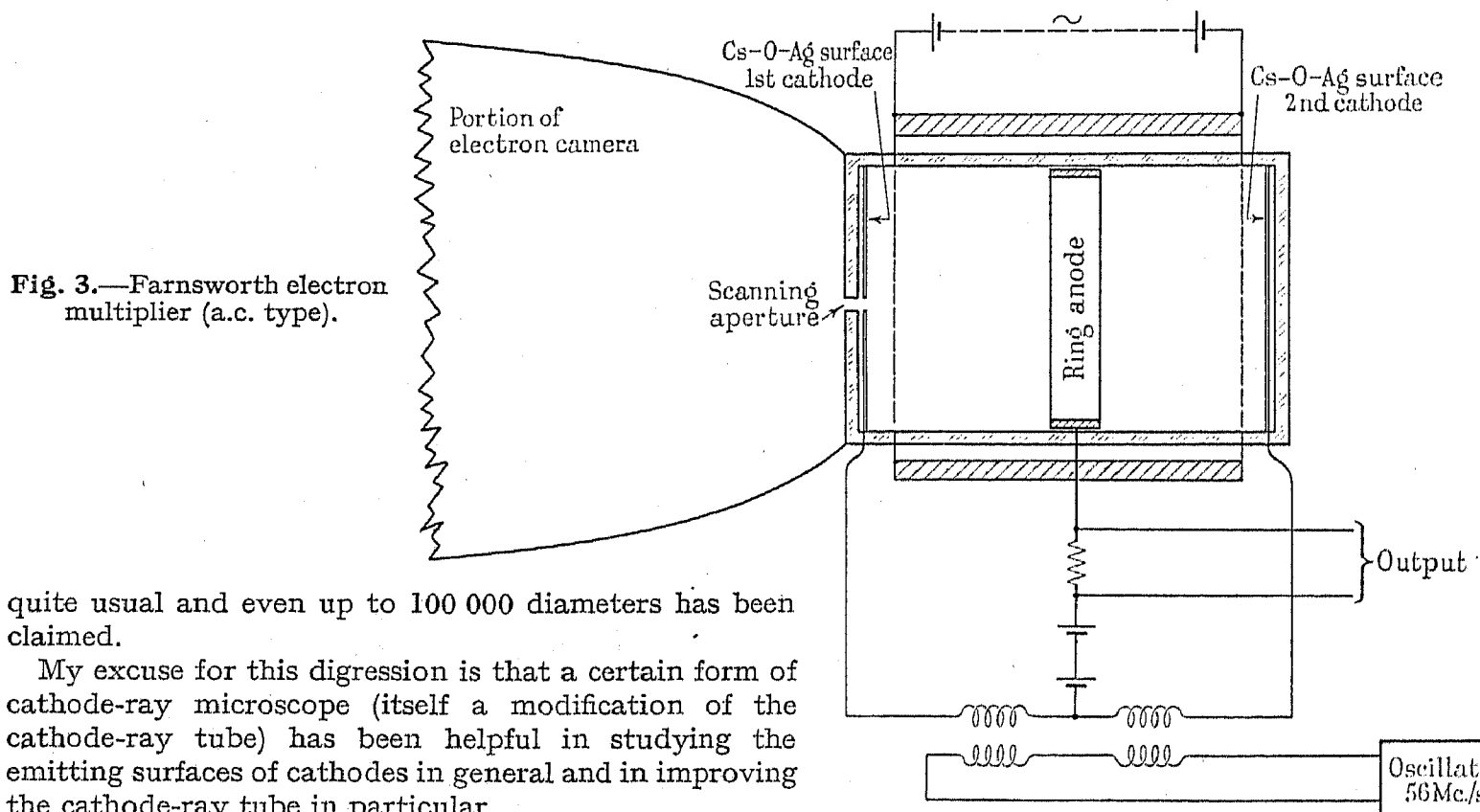


Fig. 3.—Farnsworth electron multiplier (a.c. type).

quite usual and even up to 100 000 diameters has been claimed.

My excuse for this digression is that a certain form of cathode-ray microscope (itself a modification of the cathode-ray tube) has been helpful in studying the emitting surfaces of cathodes in general and in improving the cathode-ray tube in particular.

Focusing

The cathode in the gun of the television camera, which is usually indirectly heated, emits a stream or beam of electrons. This beam can be accelerated and focused at will by means of discs and cylinders mounted coaxially and maintained at various potentials, some of which are adjustable. It is essential to produce exactly the size of

but in Fig. 4 is shown in sectional form a comparison between the Emitron and the super-Emitron, which latter, although in use, is still being improved.

Research workers were concerned at only getting 5-10 % of the possible theoretical increase as a result of the "storage" principle, and it was considered that separating the two functions of photo-emission and charge

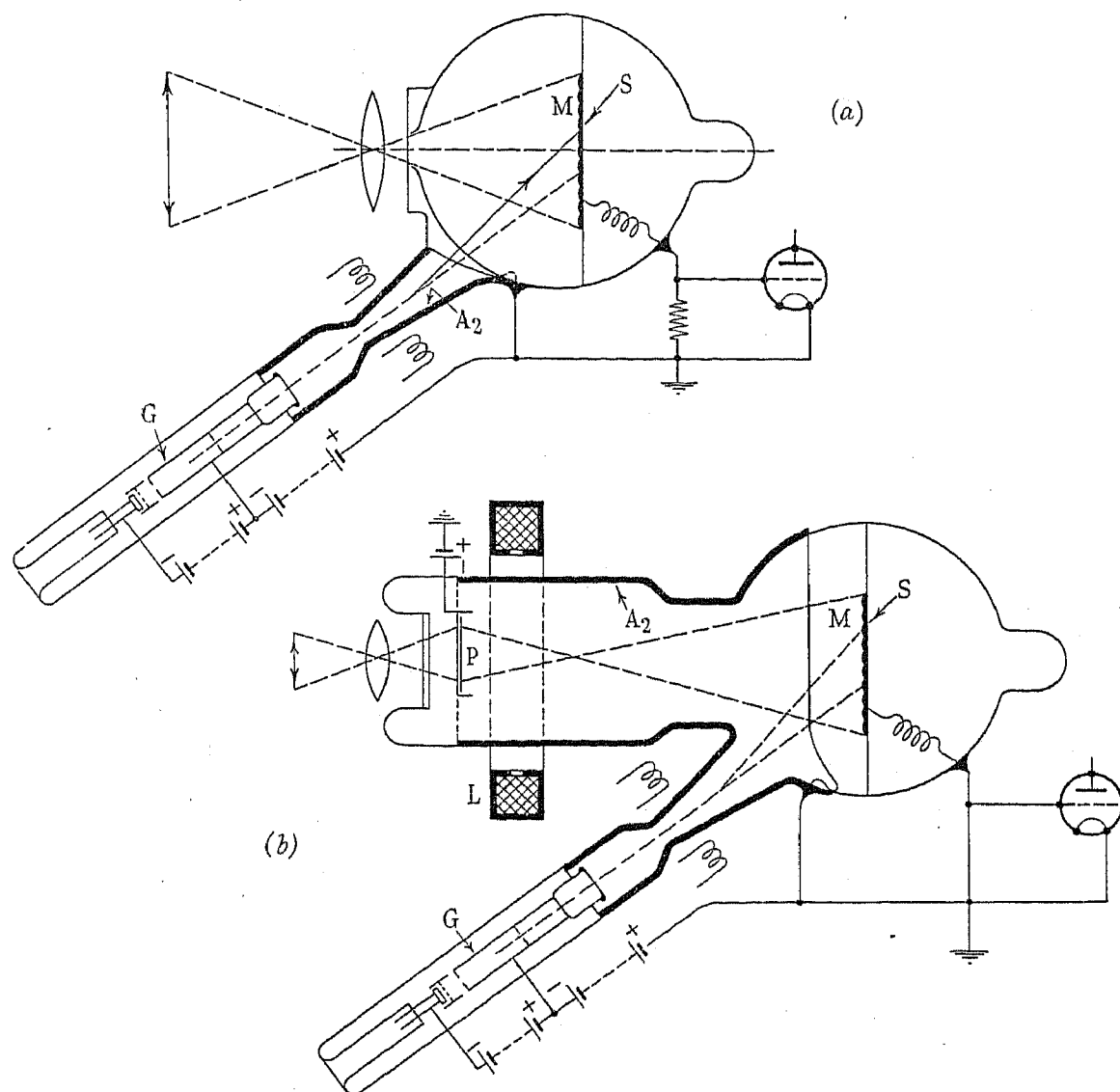


Fig. 4.—Comparison of (a) Emitron and (b) super-Emitron.

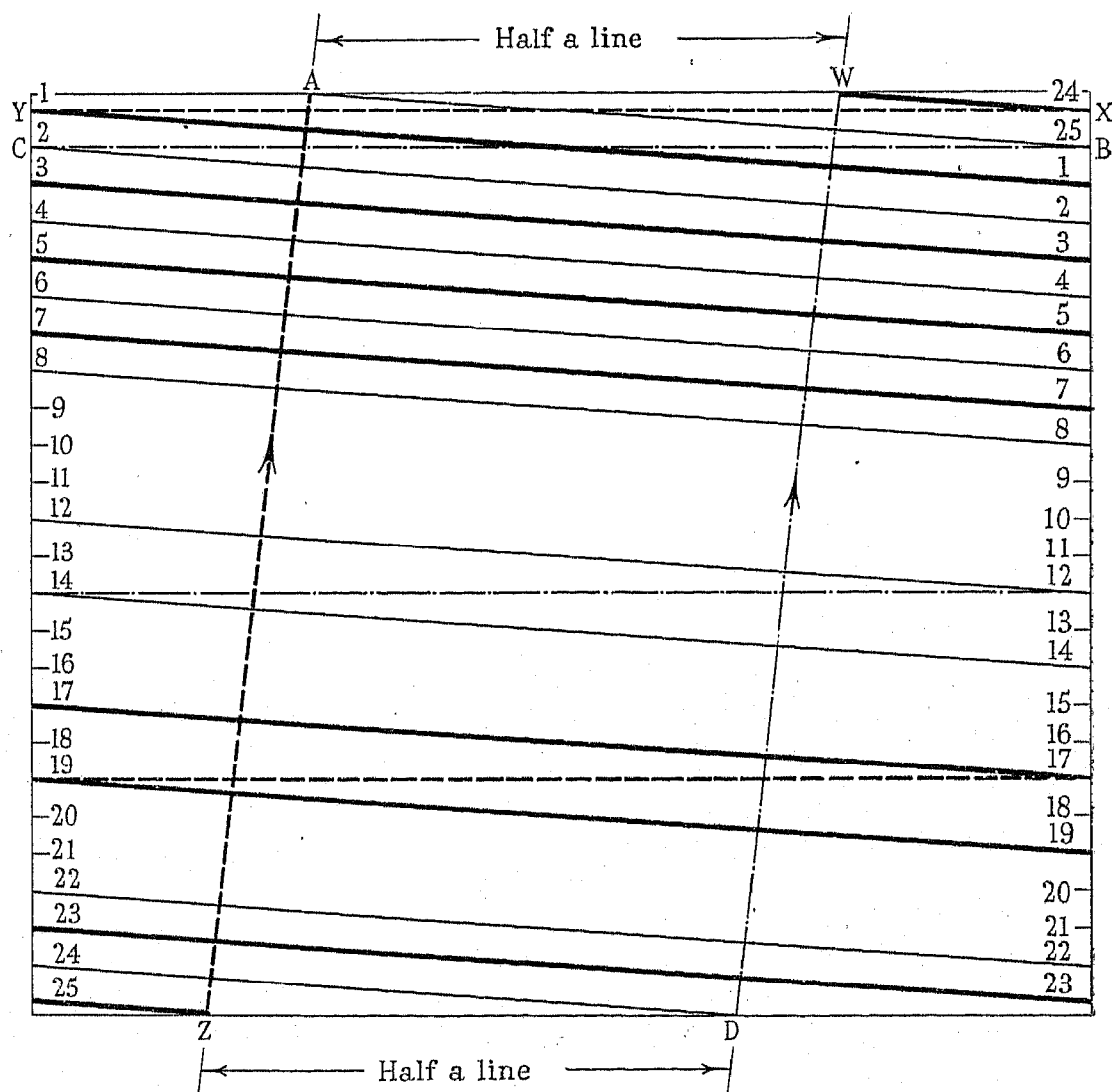


Fig. 5.—Interlaced scanning.

storage might improve things. Time does not permit me to enter into details, but in the super-Emitron the optical image is focused on to a transparent photo-emissive surface, P (which is continuous and not a mosaic), and the electron emission from this surface (which of course varies in accordance with the light and shade of the image) is focused electron-optically on to the mosaic M. This mosaic is not sensitized photo-emissively, but secondary emission still takes place.

The enormous number of small condensers store the charge produced by the electron image. The scanning by the cathode-ray beam, and the restoration of the potential equilibrium of the elements, are as before. The photo cathode P is more efficient because it is con-

Interlaced Scanning.

The actual scanning operation is as shown. Provided the line and frame traversals are regularly recurrent and have the correct frequency ratio (2 frames = odd number of lines) an interlaced picture will result.

Cables

Coaxial cables such as have been laid from London to Birmingham, Manchester and Newcastle, are subject to mutual and external interference up to about 60-100 kc./s., and as for television signals the transmission of 0-2½ Mc./s. is essential the signals have to be raised to a higher frequency level for transmission over these cables.

It was for this reason that a special balanced-pair cable

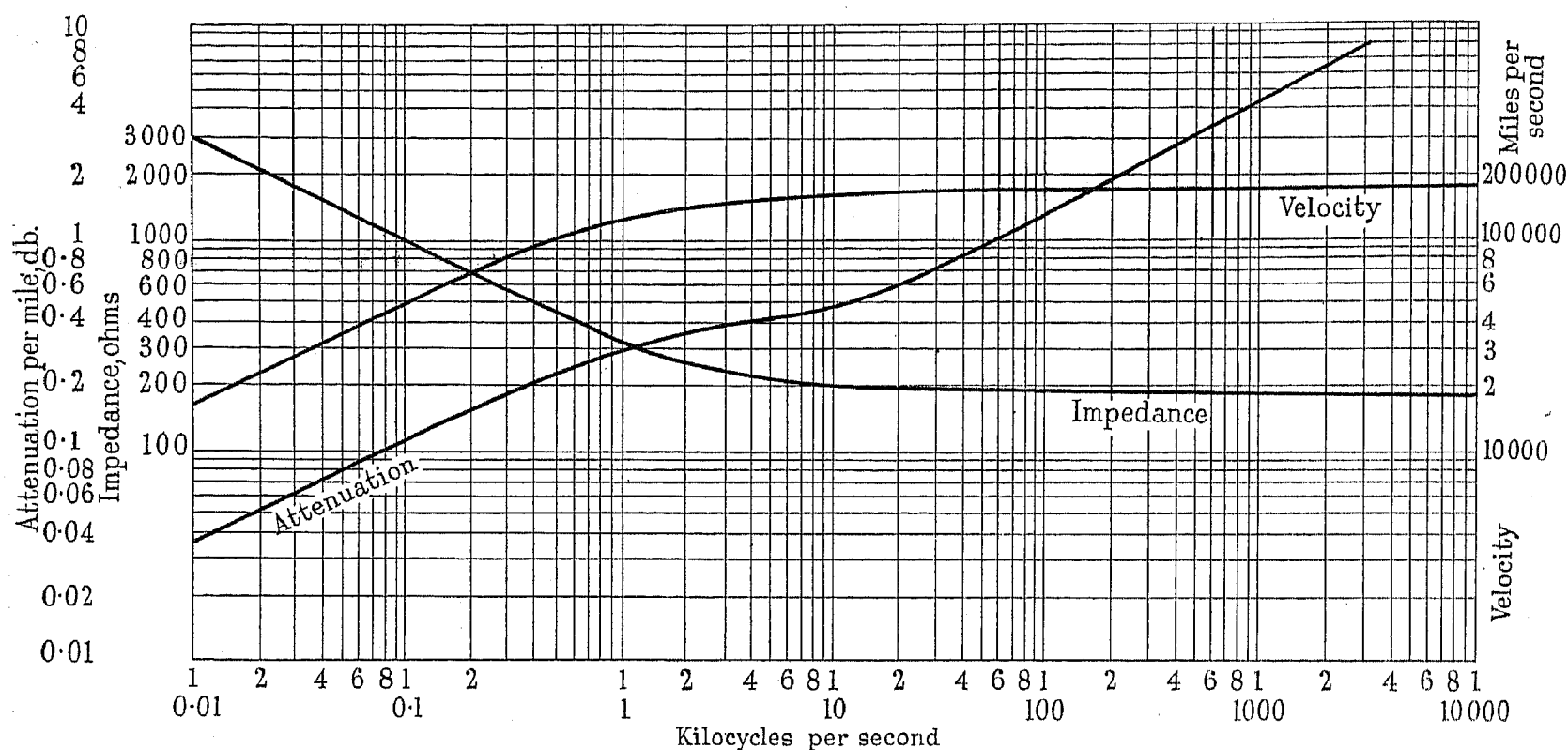


Fig. 6.—Transmission characteristics of twin cable.

tinuous, and the charges are multiplied by secondary emission from the mosaic.

Very appreciable increases in overall sensitivity have been attained, but further developments are in hand, particularly with a view to securing secondary emissions one or more times before reaching the mosaic.

The Time Base.

The unit for generating the deflecting or scanning potentials is called the time base. For 405-line 25-picture transmission the impulses for horizontal deflection are at a frequency of 10 125 per sec. (25×405), and assuming 50 frames per sec. and interlaced scanning the frequency of the impulses for vertical deflection is 50.

As these are applied simultaneously a very slightly inclined scan is produced. The velocity of the forward movements is about 2 miles per sec. The fly-back to start the next line is at 10 times or more of the forward speed. During this fly-back the beam has to be blacked out.

To achieve interlaced scanning the odd lines (W, X, Y, Z, A, in Fig. 5) are scanned first and then the even lines (A, B, C, D, W). The flyback after each vertical scan takes place at the end of each 202½ lines ($10\ 125 \div 50$).

with self-centring conductor (interference-free type) was designed and laid from the Alexandra Palace to Broadcasting House and numerous places of importance and interest in London, about 14 miles of cable in all.

Fig. 6 shows the attenuation, velocity and characteristic impedance over the range 10 c./s.—3 Mc./s.

This cable is suitable for television in 8-mile repeater sections, and therefore equalizers and amplifiers are provided at Broadcasting House and Alexandra Palace.

Between these last-named points both coaxial and balanced-pair cables have been laid. Between Berlin and Leipzig two cables are used with one coaxial pair in each—one for go and one for return—and between New York and Philadelphia there are 2 coaxial pairs in one cable. The London-Birmingham, etc., cables have 4 coaxial pairs.

RECEIVERS

Receiving aerial

Two radio carrier waves have to be received, one at 45 Mc./s. modulated from 0 up to 2½ Mc./s., and the other at 41.5 Mc./s. modulated from 30 up to 10 000 c./s.

The simplest aerial consists of a straight conductor about half a wavelength long. It is usual to use the

same aerial for both, so chosen as to resonate between the two frequencies concerned.

Sound and vision, each on its own wavelength, are picked up by the single aerial.

Receiver Circuits

They may then be amplified together and led to an oscillator or frequency-changer, which performs the combined function of separating sound and vision and at the same time converting them to lower frequencies which are more easily handled and amplified. This is the well-known supersonic heterodyne principle of frequency conversion, beating one frequency against another and employing resonant circuits to separate the resulting beat frequencies which, by a suitable choice of one of the oscillators, are made to suit the desired purpose. Sound then pursues its course to the loud-speaker as in a broadcast receiver.

The combined vision and synchronizing signals, after further amplification, again have their frequencies changed downwards to their original values. This is

emitting light. The beam must be focused to a "spot size" in accordance with the number of lines employed.

Suitable impulses generated locally in a "double time base" are applied to the deflecting coils or plates of the gun to produce the vertical and horizontal scans. Now the amplified electrical vision signals are applied to the grid of the gun, and varying its potential controls the number of electrons arriving at the screen, and hence the brightness of the spot, in accordance with the light and shade in the object or scene. At the same time the "line" and "frame" synchronizing signals lock the horizontal and vertical scanning impulses into step with the cathode-ray tube in the camera. In conjunction they thus reproduce a faithful replica of the original scene.

The light variation produced must be a linear function of the input signal voltages, and this must be achieved without varying the focusing or the velocity of the beam, and conversely the brightness of the spot must not be affected by the focusing or scanning arrangements. Very careful circuit design is necessary to this end.

The synchronizing impulse is also used to black-out

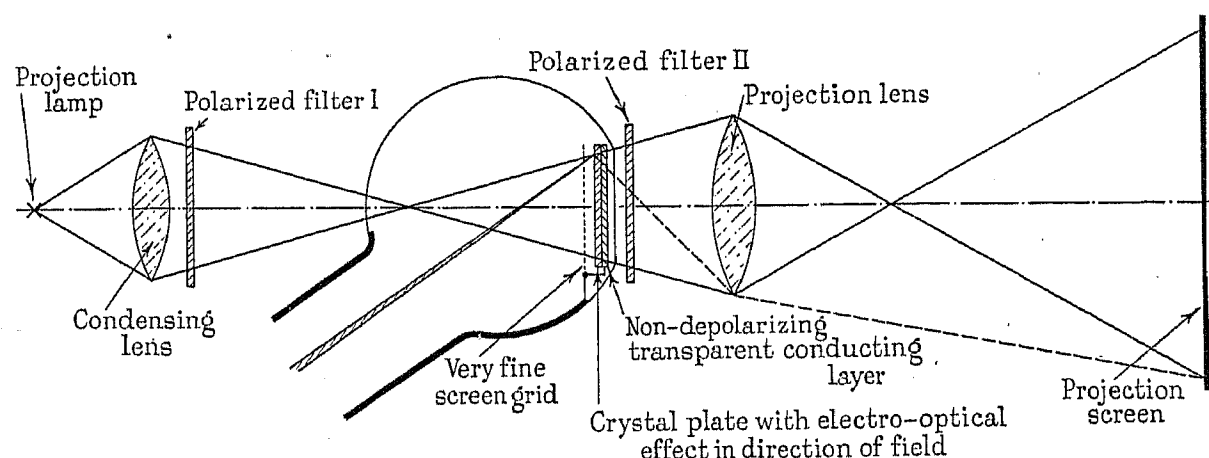


Fig. 7.—Ardenne cathode-ray tube—transmitted light control.

the well-known process of demodulation or detection by a rectifier circuit.

The next device is an overloaded valve and resonant circuit which separates the synchronizing signals from the picture signals. The synchronizing impulses are now passed through suitable filters to separate the "line" frequency pulses from the "frame" frequency pulses.

A special technique has had to be developed to obtain even attenuation over such a very wide frequency band, which amounts to 0 to 2 500 000 cycles in each side band in the case of the vision signals. In fact carrier frequencies have gone up 30 times and width of side bands up to 250 times as compared to old values.

REPRODUCTION

Whatever arrangements are adopted up to this point, they are common to any of the many possible methods of reproduction.

Cathode-Ray Tube

Taking first the solution adopted in the majority of commercial television receivers to-day, namely the familiar cathode-ray tube with its fluorescent screen, a locally produced stream of electrons is shot a high speed from the electron-gun on to the fluorescent screen which acts as a transducer, absorbing electrical energy and

the fly-back stroke by biasing the control electrode negatively.

Other Systems with C.R. Tubes

The foregoing is a "creative" method, and also, although the decay of fluorescence is somewhat slow, there is no deliberate attempt at storage.

In one system,* to achieve storage, the fluorescent screen is abandoned for a special screen, the opacity or reflecting power of which varies under the action of the scanning beam. The idea is for the acquired properties of the screen to remain constant for a frame period and then to be wiped out by a second scanning beam which travels just ahead of the signal beam and so leaves the way clear for the next frame. An alternative is to arrange for a few lines ahead to be wiped out by the line fly-back stroke, in which case only one beam is required, but rather complicated circuits are necessary for this.

The optical arrangements would be as in Fig. 7 in the case of the "opacity" system, and as in Fig. 8 in the case of the reflecting system. It would also allow light control to be adopted.

Optical-Mechanical Systems

Of the innumerable methods of light control that have been tried, and on many of which much ingenuity has

* Von Ardenne's.

been spent, few have survived to meet the exacting conditions of high definition television, and only two electro-optical methods, namely the Kerr cell and supersonic light control, need be considered here.

The Kerr cell is used with polarized light. As is well known, light is propagated by transverse vibrations in all directions at right angles to the direction of propagation. Now certain crystals such as calcite (a transparent crystalline form of calcium carbonate) have the property that only light vibrations in one particular plane are transmitted through them, and the emergent light is then said to be polarized. A specially arranged combination of calcite (Iceland spar) and Canada balsam, known as a "Nicol's prism," is used for this purpose. If a second prism is so placed as only to pass light in a plane at right angles to the first, then no light will pass.

Now certain liquids, such as carbon disulphide and nitro-benzene, when subjected to electric stress become "bi-refrangent." A Kerr cell (of the multi-plate type) consists of very thin interleaved electrodes immersed in nitro-benzene. If such a cell is placed between the two Nicol's prisms and the voltage across the cell is gradually increased the plane of vibration of the light which has

a piezo-electric crystal. The crystal is energized by a locally generated high-frequency oscillation at about 10 Mc./s., and this must be the same as the natural frequency of the crystal.

This produces in the liquid a series of supersonic waves which are propagated at the velocity of sound in that particular liquid. The wavelength is very short, being of the order of that of light. Lenses are placed on either side of the container, and light is passed through the combination in a direction transverse to the direction of propagation of the supersonic waves. The oscillator or carrier frequency is modulated by the incoming vision signal, and this controls the amplitude of the waves. This in turn sets up diffraction, which varies the intensity

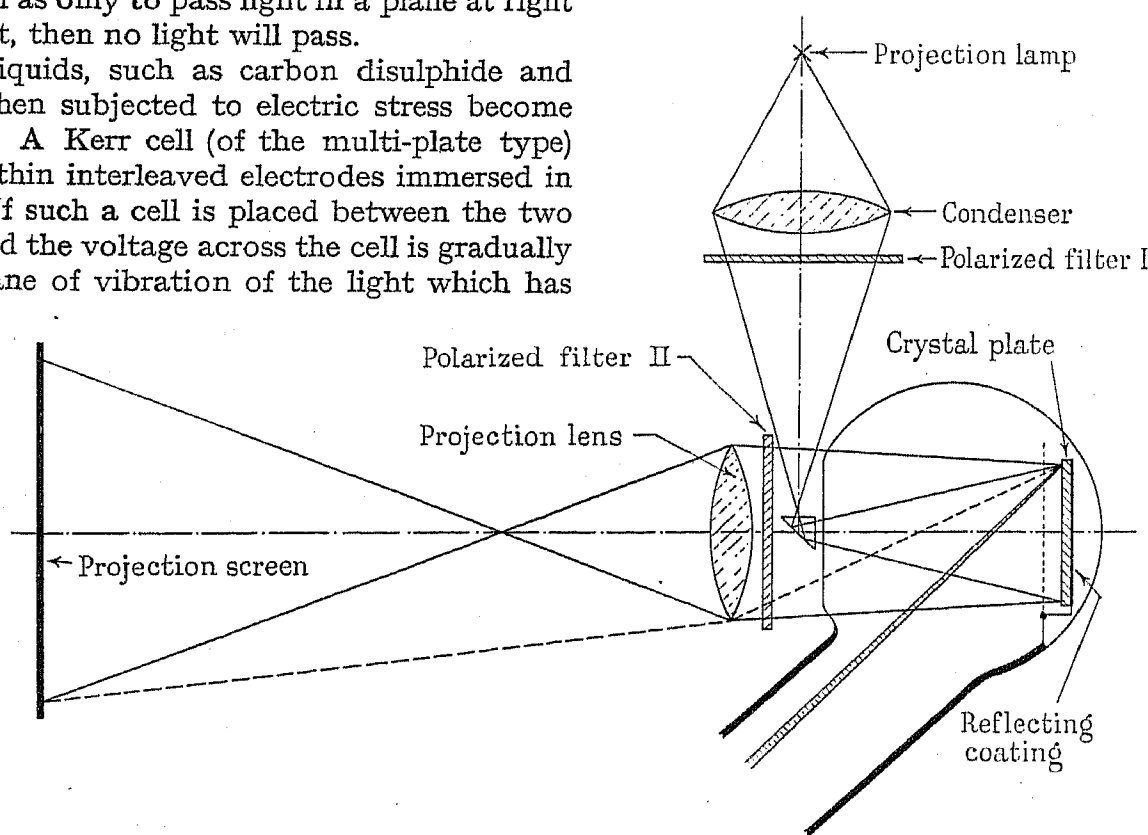


Fig. 8.—Ardenne cathode-ray tube—reflected light control.

passed through the first prism will be distorted first into an ellipse, which becomes a circle and finally a line of vibration at right angles to the original direction. Thus more and more light is available to pass through the second prism, and over a certain range the variations of the final light beam through the combination are proportional to the voltage variations in the applied television signal.

The obvious advantage of any control method is that a powerful source of light can be used instead of being dependent on the small amount of light produced in "creative" methods. An improved "double image" Kerr cell has been developed which passes at least twice as much light as the ordinary Kerr cell.

Scophony System

There are two fundamental principles involved in this ingenious system, (a) supersonic light control and (b) split focus.

Supersonic Light-Control (see Fig. 9).

This consists of a transparent container filled with a liquid, such as water or kerosene, at one end of which is

of the emerging beam. The amplitude of the supersonic waves will vary from point to point, i.e. they will be modulated in accordance with the modulations of the vision signal, and at any moment there may be a train of waves corresponding to, say, 200 picture elements. By means of suitable lenses and scanners an image of the illuminated light control itself can be formed on the screen the width of one line of the picture and the length of the liquid column of the light control. Now the scanner which is between the light control and the screen must be rotated until it follows exactly the speed of propagation of the supersonic waves in the liquid. The modulation stored in the supersonic waves then becomes visible on the screen, and in effect a large number of spots are used simultaneously, increasing the overall light efficiency say 200 times (the maximum possible is theoretically 500 times).

Split Focus.

By using cylindrical instead of spherical lenses the beam of light is focused on to the scanner surface in one transverse direction only, i.e. only in the plane at right angles to the direction of scanning. In the other trans-

verse direction, i.e. in the scanning plane, the beam is brought to a focus on the screen by means of another cylindrical lens. Hence the beam is brought to a focus in the two perpendicular planes at different stages of the optical process, and the focus is said to be "split." The advantage is that for the same size of scanners a much greater aperture of the optical system can be usefully employed, and vice versa.

Further details of the Scophony system are included in the Section entitled "Review of recent progress."

As regards film transmission, the intermittent scanning method which made use of the "memory" of the camera tubes has given place to the mechanical-optical compensation system with continuous-motion projectors.

REVIEW OF RECENT PROGRESS AND PRESENT POSITION America

After much discussion it has been agreed to standardize on the suppression of all but 0.75 Mc./s. of one sideband,

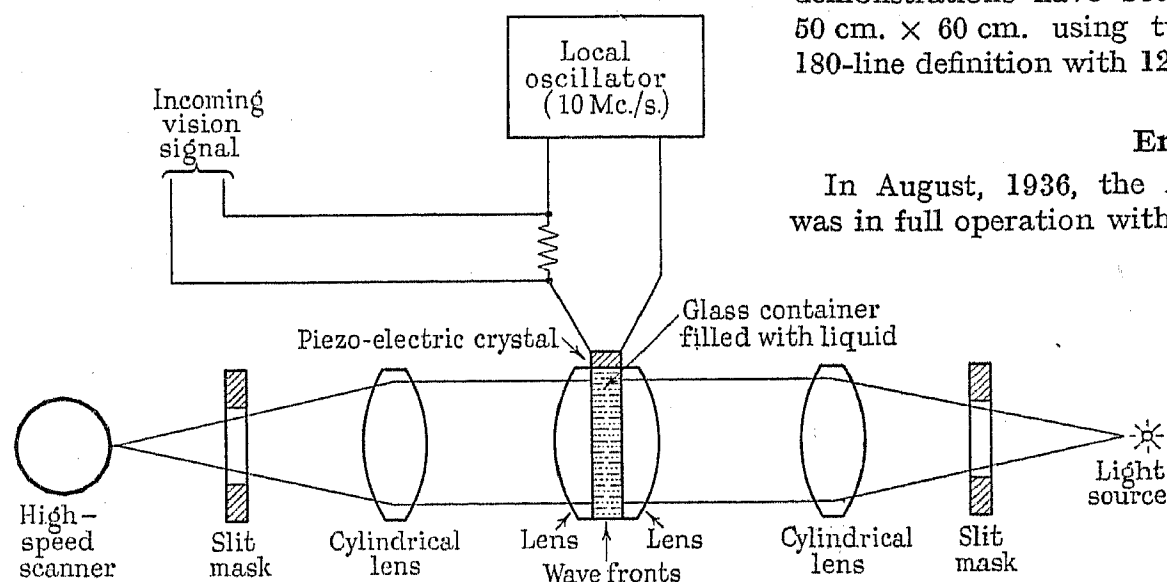


Fig. 9.—Supersonic light control.

the other sideband naturally being transmitted in its entirety.

What is known as "negative modulation" has been decided on. In this, zero carrier is used for white, 70 % carrier for black, and 70–100 % carrier for synchronizing signals.

In England and Germany "positive modulation" is preferred.

France

In France, although experimental low-definition transmissions have taken place since 1935 from the Eiffel Tower, the high-definition transmitter was not finished until 1937, when demonstrations were given at the Paris Exhibition. Even now it is understood to be more in the nature of a big laboratory experiment than a regular public service. The vision transmission is on 46 Mc./s. with 30 kW (peak) power, and the sound channel is on 42 Mc./s. Home receivers cannot be made available to the public because no standards have been fixed, four different transmissions taking place from 440 to 455 lines.

Germany

Since 1932, 180-line 25-frame television has been trans-

mitted in Berlin, free viewing facilities being provided in about 30 public viewing rooms.

Television Telephony.—There are transmissions on 180 lines, 25 frames, and also 150 lines, 50 frames, between Berlin–Leipzig, Nürnberg and München. Coaxial cables have been commenced to Hamburg and Vienna, and are utilized as follows:—

0 to 1 Mc./s. for 200 telephone channels by carrier wave.

1 to 2 Mc./s. for television-telephone (lower sideband only).

2 to 4 Mc./s. for television (lower sideband only).

Transmission.—The Nipkow disc is now rarely employed except for films. Several cathode-ray-tube types, including a super-Iconoscope, are now ready for service, as are also electron multipliers, which are used in connection with spot scanning of persons, as in television-telephony.

Large Screen Pictures.—Special attention has been given to this and screens up to 10 m. square with good illumination have been used. Amongst other investigations colour television is receiving special attention; demonstrations have been given recently on a screen 50 cm. × 60 cm. using two fundamental colours and 180-line definition with 12½ pictures per sec.

England

In August, 1936, the Alexandra Palace transmitter was in full operation with an increased power of 17 kW

with regular programmes to the public, thus giving the first public television service in the world.

On the 12th May, 1937, the Coronation procession was televised with great success, this being the first outside television of importance. Although the light was bad telephoto lenses were used. The mobile control vans were also used.

In June, 1937, the Television Exhibition opened at the Science Museum, South Kensington. From the latter part of 1936, onwards, programmes have been given for 3 hours daily, and film transmissions have been used very little.

At the Olympia Wireless Exhibition in September, 1937, 14 British firms showed television receivers, the prices ranging from £38 to £125.

By 1938 the programmes had been improved, a number of outside events of national importance and sporting interest being included.

Theatres.—On the 21st February, 1939, monthly transmissions were commenced of straightforward televising of an ordinary performance from the Coliseum stage. This theatre was the first in the world to be permanently wired for television.

On the 27th March, 1939, a scene was televised from His Majesty's Theatre, and it is hoped to include a transmission once a month.

Cinemas.—A stir was created in the wireless and cinema worlds by the televising of the Boon-Danahar fight at Harringay on the 23rd February, 1939; the transmission was projected on the screen at three of London's cinemas.

An audience of 1 200 saw it at the Marble Arch

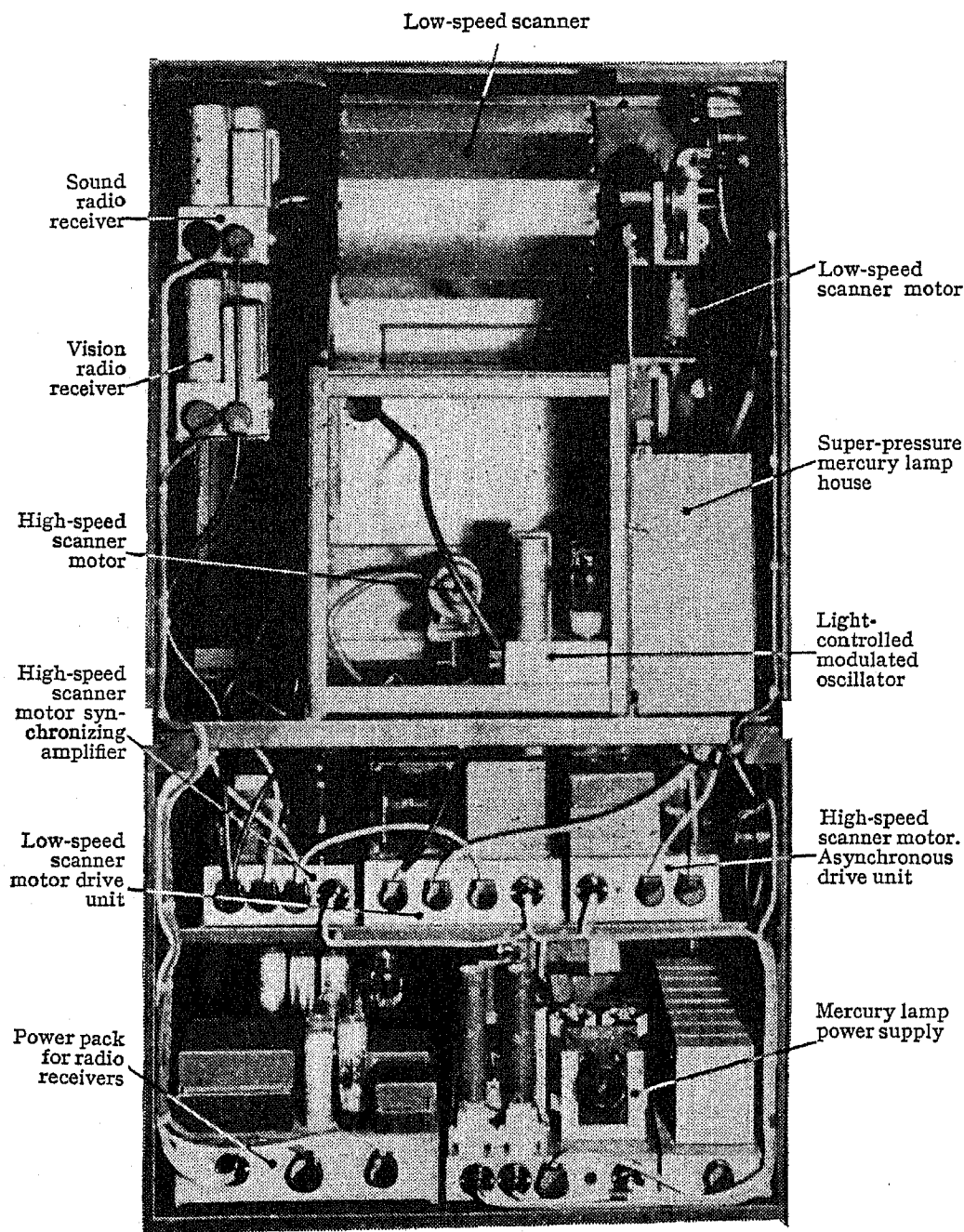


Fig. 10.—Interior of Scophony home receiver.

Pavilion, where a screen 15 ft. $\times$ 12 ft. was used. This was the first time that the public had been able to pay to see a television projection.

The transmission was also seen at the Tatler Theatre on a screen 12 ft. 6 in. $\times$ 10 ft. Transmissions have been received at this theatre for the past 12 months on a screen 8 ft. $\times$ 6 ft. 6 in.

At the New Monsiegnur News Theatre the transmission was shown by the Scophony optical-mechanical big-screen system.

On the 16th March, 1939, another championship fight was televised and was shown at the same theatre with excellent results.

RECENT DEVELOPMENTS

I have inquired into this question of large screen presentation of television and have received some most interesting replies.

The Baird Co. inform me that they have abandoned mechanical methods in favour of electronic equipment and have aimed at increasing the size and brightness of the picture. In the ordinary cathode-ray receiving tube the fluorescent screen is normal to the electrode assembly axis, and in viewing the fluorescent image from the opposite side of the screen there is a serious loss of brilliance due to the light having to pass through the thickness of the fluorescent material and the binding material that secures it to the inner surface of the tube. A special tube has therefore been developed with a separate fluorescent screen mounted inside the tube at an angle to the electron gun in a similar position to the mosaic screen in an Emitron camera cathode-ray tube. The much greater brilliance on the surface of the fluorescent screen which faces the electronic beam can now be taken advantage of, and the projection lens is mounted directly in front of this screen with only a thin plain glass wall between.

Trapezium distortion is corrected electrically in the same way as in the camera tube. As the frame scan progresses from the bottom to the top of the screen a linear decrease of the line scan amplitude occurs at such a rate as to neutralize the effect, but as we need maximum beam current in this case we cannot obtain depth of focus by providing a small aperture. Therefore change of focus which would otherwise occur as the beam travels from the top to the bottom of the inclined screen has also to be corrected electrically. Moreover, to obtain the degree of fluorescence necessary for a big and bright picture the voltage is increased to 40 000 or 45 000 volts and the actual beam current is about 300–400 μ A, compared with about 0.1 μ A in camera tubes.

An improved screen powder has had to be developed to withstand this terrific electronic bombardment and to obtain greater light intensity. Salts must be of

extreme purity, and minute but accurately adjusted quantities are added of the order of about 1/10 000 of 1 %.

Naturally, special designed scanning circuits and modulating arrangements have been necessary, and special attention has had to be paid to an improved vacuum to avoid ionization at these very high voltages. Also the insulation of the high-voltage anode assembly has had to be increased.

Commercial apparatus is now being rapidly installed in the Gaumont British cinemas with screens 15 ft. $\times$ 12 ft. and with a picture brilliance comparable with that obtained by ordinary cinema film projection. The receiver is placed in the centre of the stalls, several feet

away from the screen, and contains the necessary controls. A silver-surfaced screen is raised into position

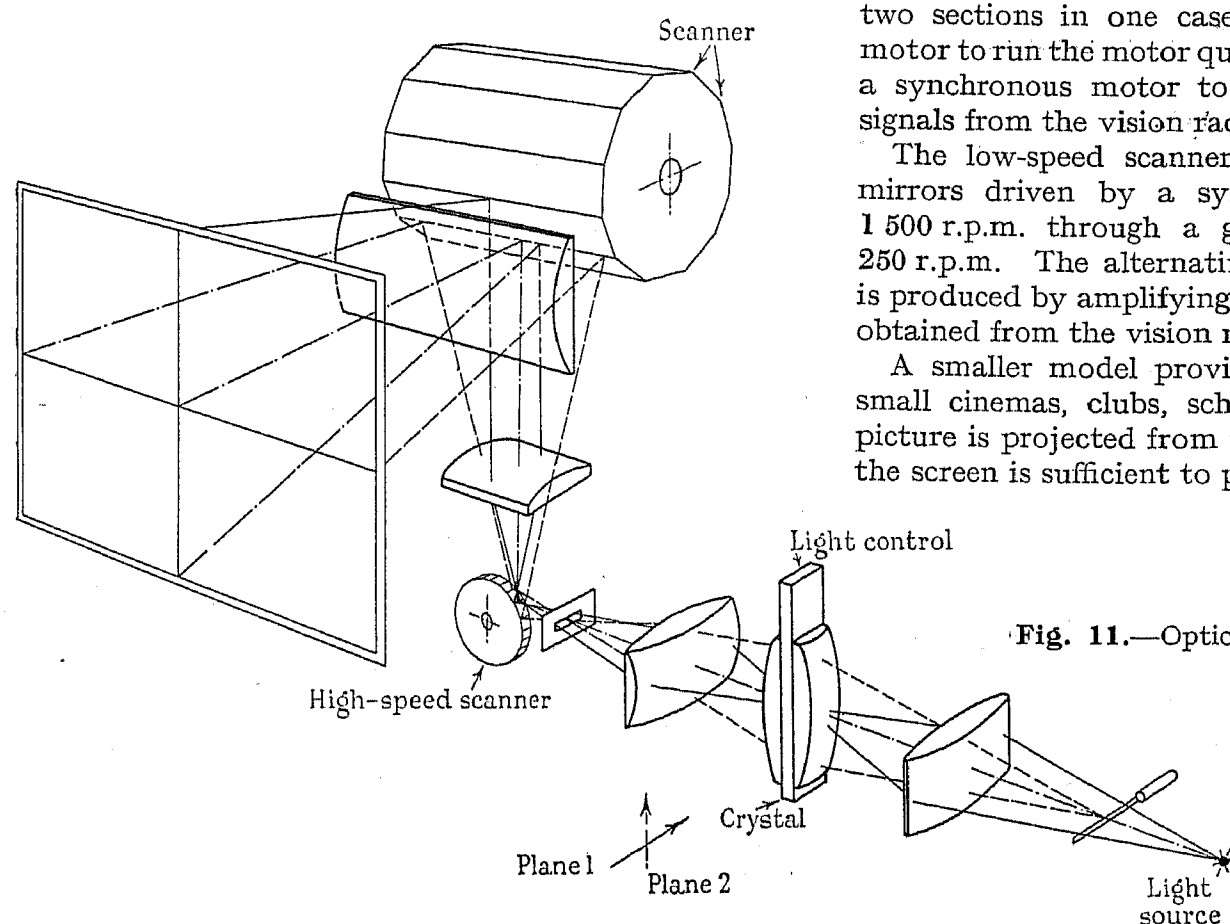


Fig. 11.—Optical diagram of Scophony receiver.

through a trap-door on the stage. Two cathode-ray tubes are kept running continuously, one as a standby.

The H.T. supply is derived from a special rectifier with an output of 60 kV at 10 mA. It is housed in a safety cage with the usual automatic safety devices. The total consumption is 2 kW, and the sound frequency response is 30–20 000 c./s., which is the maximum that can be appreciated by the human ear. The firm of Scophony, Ltd., have set the pace for large-screen television and are pioneers in providing home receivers with large pictures (24 in. × 20 in.) of a pleasant black and white colour. Fig. 10 shows one model with the back removed.

The novel optical principles previously referred to are shown in Fig. 11. They have resulted in simpler and smaller apparatus. By their means light can be modulated from any desired source. For example, 1 watt of modulated current can control the light from a 40-ampere arc. Moreover, the latest development in illumination technique and the most efficient and brilliant light source known is the special super-high-pressure mercury lamp. The type used in the home receivers consumes $3\frac{1}{2}$ amp. at 80 volts, or about 300 watts. The brilliancy is higher than that of a standard cinema carbon arc.

The output from the vision radio receiver is led by a coaxial cable to the "light control drive unit."

The radio-frequency amplifier valve is connected to the quartz crystal on the light control cell and is grid-modulated by the video amplifier. The full 5 Mc./s. of the two sidebands is fed to the light control.

The high-speed motor for the small-mirror line-scanning polygon has been specially developed (see Fig. 12). It runs at 30 375 r.p.m. and great attention has of

necessity been given to precision balancing. It is silent and cannot be heard outside the cabinet, and its life is at least equal to that of a radio valve. It is composed of two sections in one case, one being an asynchronous motor to run the motor quickly up to speed, and the other a synchronous motor to which are fed synchronizing signals from the vision radio-receiver.

The low-speed scanner (see Fig. 13) consists of 12 mirrors driven by a synchronous motor running at 1 500 r.p.m. through a gear-box to a final speed of 250 r.p.m. The alternating current to drive the motor is produced by amplifying the frame synchronizing pulse obtained from the vision radio-receiver.

A smaller model provides a picture 6 ft. × 5 ft. for small cinemas, clubs, schools, etc. In this model the picture is projected from the rear, and the brightness of the screen is sufficient to permit subdued illumination of

gangways. The voltages do not exceed those used in a small cinema.

The public-hall model resembles in appearance a standard cinema projector and can be handled by any cinema operator.

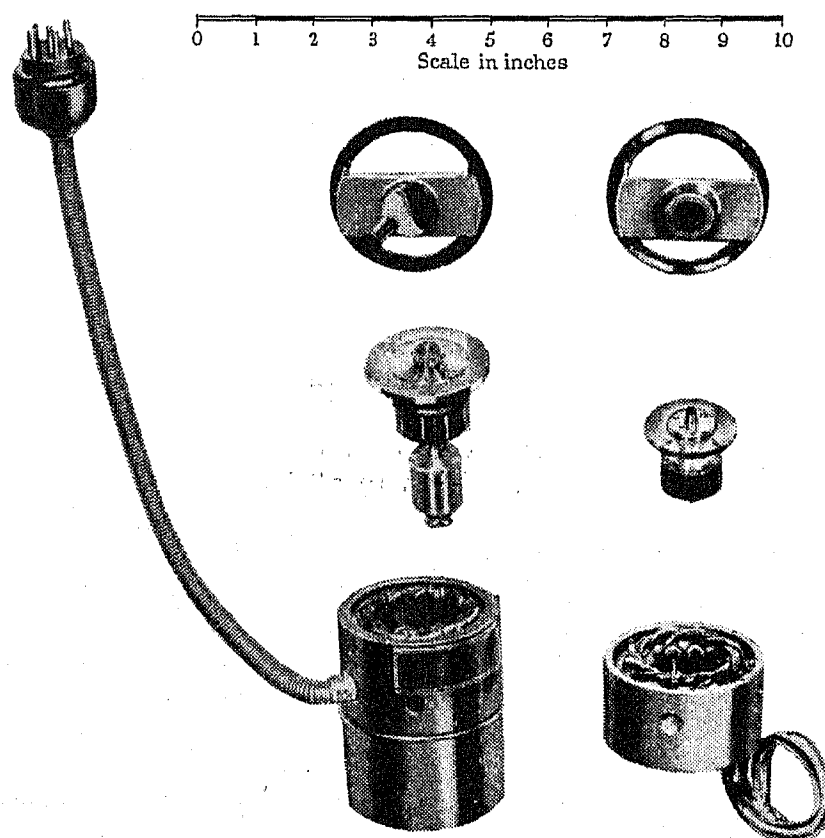


Fig. 12.—Standard high-speed scanner motor (left), and new type of motor in course of development (right).

To conclude, I cannot do better than quote the end of Baird and Co.'s letter to me.

"There can be no gainsaying that television, the most wonderful invention of the century, is a British scientific triumph. The Alexandra Palace high-definition transmitter opened in 1936 was the first station to broadcast a regular programme service, and the British radio trade designed and produced the first commercial receiver sets for the home.

"Britain has by her enterprise set a model to all the world to follow, and a consideration of the influential part

of television in Germany and for copies of certain German technical journals and papers, including examples of experimental colour television which I have been unable to reproduce in this Address. I also wish to acknowledge information received from the Baird Television, Ltd., and from Scophony, Ltd., as well as to record my thanks to the Marconi Co. for the loan of some of the photographs. Moreover, I am indebted to numerous books and papers (set out in the Bibliography) for much of the information contained in the Address.

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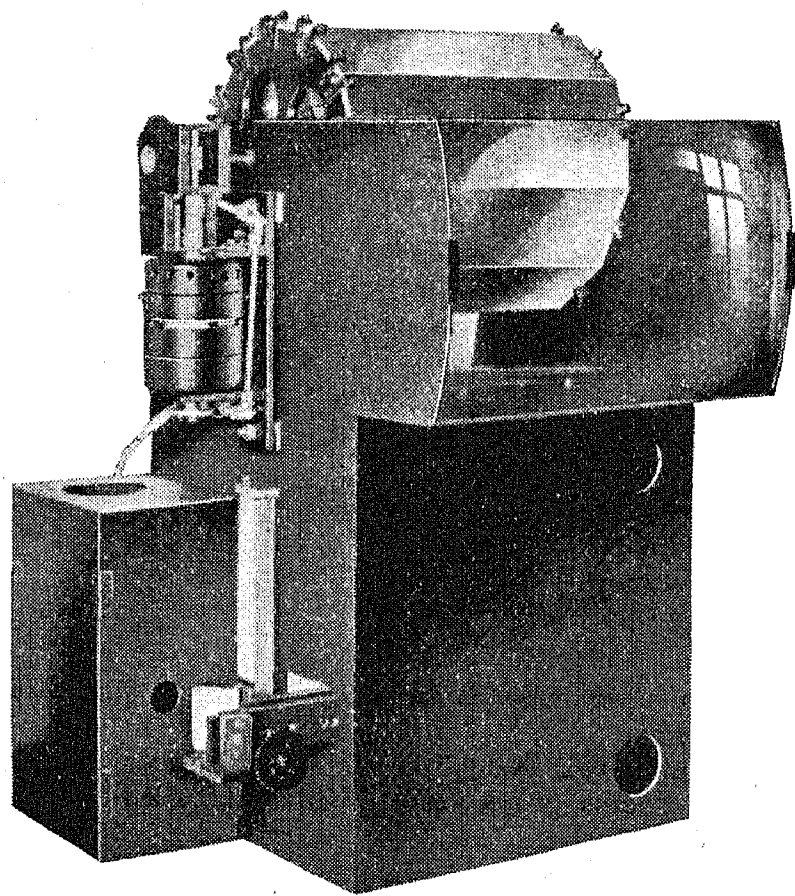


Fig. 13.—Optical chassis of Scophony receiver.

that television is destined to play in the future as a means of communication and instruction, no less than as a medium for entertainment, leaves no doubt of the paramount importance of retaining the lead in this new industry. As a result of pressure from both the cinema and radio trades the experimental work now being conducted for the purpose of extending the service to the Provinces is being expedited and a definite decision on this matter is expected in the near future. This provincial extension would give direct employment to many and in the immediate future to a wide section of those trades interested in television in all its aspects. These benefits would be additional to the present major objective, which is to secure for the British television industry the dominance of the home and export markets to which its pioneer efforts entitle it."

ACKNOWLEDGMENTS

I wish to acknowledge my indebtedness to Herr H. Pressler for information as to progress and development

THE ELECTRICAL STABILITY OF TUBULAR INDUCTANCE COILS WITH DEPOSITED CONDUCTORS*

By H. A. THOMAS, D Sc., Member.

(Paper first received 1st August, and in revised form 27th December, 1939.)

(1) INTRODUCTION

In previous papers† the conditions necessary to obtain inductance coils of high electrical stability with respect to temperature variation have been formulated. Tests on two coils (referred to as A and B) with ceramic formers and deposited conductors indicate that to obtain a low temperature coefficient of inductance which is sensibly independent of frequency it is desirable to use a conductor of ribbon section deposited flatwise on a former of low temperature coefficient of expansion. Furthermore, it has been shown that the turn spacing should be as large as possible, so that an appreciable current redistribution can occur with frequency variation without producing an appreciable change of inductance.

To test whether this conclusion is substantiated in practice, measurements have been carried out on three experimental coils in which the turn spacings were different while the other dimensions were made similar.

(2) CONSTRUCTION OF TEST COILS

Since it is difficult to reproduce accurately the thickness of a deposited film, it was decided to construct three coils having fused-silica formers in which the metal conductor is machined to a definite thickness. These formers were all ground to the same outside diameter and spiral grooves were cut in each of the same width but with different axial turn spacing. The former was then sprayed with copper to a depth considerably in excess of the required thickness of conductor section, superfluous metal was removed between turns, and the turns themselves were reduced to the correct radial depth by machining. In this way, a reasonably uniform section was obtained, but the radial depth could not be made less than 0.1 mm.

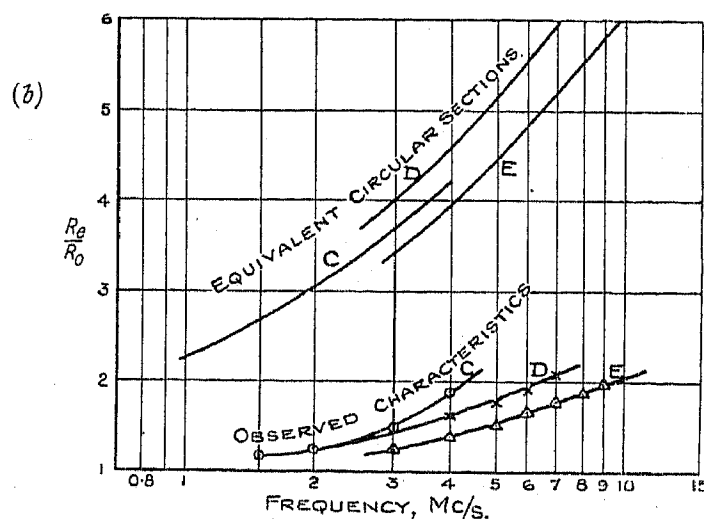
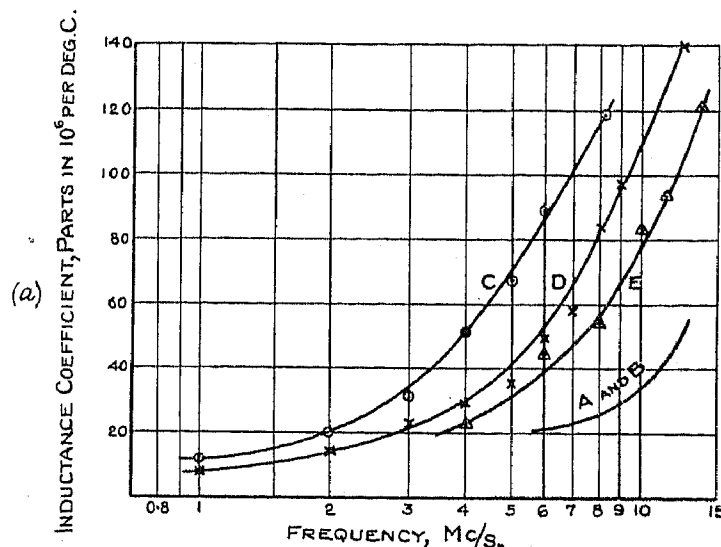
The mechanical and electrical properties of these coils (referred to as C, D and E) are given in the Table, and for comparison purposes the details of Coils A and B are reproduced from the 1939 paper.‡

(3) MEASUREMENT OF TEMPERATURE COEFFICIENT OF INDUCTANCE

The temperature coefficient of inductance of these coils was measured over as large a frequency band as possible; the results are shown at (a) in the Figure. The radio-frequency resistance was also measured, and the

ratio of the radio-frequency resistance (R_e) to the direct-current resistance (R_0) is plotted against frequency at (b) in the Figure. The theoretical value of this ratio is also plotted for a circular-section conductor of the same equivalent sectional area.

As in the previous cases of Coils A and B, it is observed that the effective resistance increases very little with



Observed characteristics of coils.

frequency as compared with the circular-section conductor. The temperature coefficient of inductance has a low value at frequencies below 2 Mc/s., but as the frequency increases the value of this coefficient increases rapidly to very high values. As the spacing between turns is increased it is noticed that the frequency corresponding to any particular coefficient increases. This is in agreement with the general deductions made in the previous paper.†

The temperature coefficient of inductance of Coils C,

* Official communication from the National Physical Laboratory.

† The Papers Committee invite written contributions, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Contributions (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

‡ H. A. THOMAS: "The Stability of Inductance Coils for Radio Frequencies," *Journal I.E.E.*, 1935, **77**, p. 702; and "The Dependence on Frequency of the Temperature Coefficient of Inductance of Coils," *ibid.*, 1939, **84**, p. 101.

† *Loc. cit.*

† *Loc. cit.*

Table

	Coil A	Coil B	Coil C	Coil D	Coil E
Diameter, mm.	30	30	68	68	68
Number of turns	23	18	28	19	14
Ratio: length/diameter	2.50	1.80	1.25	1.40	1.40
Width of section, mm.	2.00	1.50	2.03	2.03	2.03
Radial depth of section, mm.	0.0076	0.035	0.104	0.125	0.092
Axial turn spacing, mm.	3.00	3.00	3.05	5.08	7.12
Inductance, μH	6.3	4.8	30.7	13.7	7.7
Self-capacitance, $\mu\mu\text{F}$	1.6	1.4	3.2	2.4	2.3
Resistance, ohms	2.40	0.57	4.85	2.71	2.74
Natural frequency, Mc./s.	52	59	16	28	38
Permittivity of silica former	6.50	6.5	3.85	3.85	3.85
Temperature coefficient of permittivity of former material, per deg. C.	$+ 160 \times 10^{-6}$	$+ 160 \times 10^{-6}$	less than $+ 50 \times 10^{-6}$	less than $+ 50 \times 10^{-6}$	less than $+ 50 \times 10^{-6}$
Expansion coefficient of former material, per deg. C.	$+ 7.8 \times 10^{-6}$	$+ 7.8 \times 10^{-6}$	$+ 0.5 \times 10^{-6}$	$+ 0.5 \times 10^{-6}$	$+ 0.5 \times 10^{-6}$
Diameter (mm.) of equivalent circular section to give same d.c. resistance	0.150	0.260	0.520	0.568	0.488

D and E varies more rapidly with frequency and reaches considerably higher values than that corresponding to Coils A and B. This is probably due to the fact that the radial depth of section is 10 times greater than that of Coils A and B. It appears from these tests that to obtain a temperature coefficient of inductance which is small and independent of frequency it is necessary not only to use a large turn spacing but also to maintain a very small radial depth.

(4) ACKNOWLEDGMENTS

The work described in this note was carried out as part of the programme of the Radio Research Board and is published by permission of the Department of Scientific and Industrial Research.

The author wishes to acknowledge his indebtedness to his assistant, Mr. R. G. Chalmers, for carrying out the observations and to Mr. W. G. Mildenhall for his painstaking work in constructing the coils.

THE THEORY OF THE THERMIONIC DIODE*

By PROFESSOR E. L. E. WHEATCROFT, M.A., Member.†

(Paper first received 16th August, and in revised form 27th December, 1939.)

SUMMARY

Theoretical calculation is made of the space charge in a thermionic diode having cylindrical symmetry, taking account of the distributed initial velocities of the emitted electrons. Curves are given from which the theoretical volt-ampere characteristic can be found. The mathematical method is detailed in Appendices.

TABLE OF CONTENTS

- (1) Introduction.
- (2) Space-charge-limited Diode: Region of Retarding Potentials.
- (3) Saturated Diode.
- (4) Space-charge-limited Diode: Region of Accelerating Potentials.
- (5) Example of Calculation.
- (6) References.
- Appendix 1. Formal Mathematics.
- Appendix 2. Retarding Field.
- Appendix 3. Saturated Valve.
- Appendix 4. Accelerating Field.

LIST OF SYMBOLS

- a = a constant.
- $B = 2\sqrt{\pi c^2 I r_0} \frac{[m/(2e)]^{\frac{1}{2}}}{[k\tau/e]^{3/2}}$
- $B_0 = BI_0/I$
- $B_m = Br_m/r_0$
- b = a constant depending on dimensions of valve.
- $C = \left(\frac{4\sqrt{\pi}}{9B_0}\right)^{\frac{1}{2}}$ or $\left(\frac{4\sqrt{\pi}}{9B_m}\right)^{\frac{1}{2}}$ as specified in the text.
- c = a constant depending on units employed.
- d_a = cathode/anode spacing.
- d_m = cathode/minimum-surface spacing.
- e = base of Napierian logarithms.
- e = electronic charge.
- I = anode current.
- I_0 = total emission current.
- i = current per unit (anode) area.
- k = Boltzmann's constant.
- l = axial length of system.
- m = electronic mass.
- p^2 = ordinate difference between limit line and envelope (Fig. 7).

LIST OF SYMBOLS—continued.

- r_0 = radius of cathode.
- r_a = radius of anode.
- r_m = radius of minimum surface.
- S = space-charge integral.
- u = radial velocity.
- $u_r = \left(\frac{2k\tau}{m}\right)^{\frac{1}{2}}$
- u_x = radial component of initial velocity at any point of filament.
- u_y = tangential component of initial velocity at any point of filament.
- u_z = axial component of initial velocity at any point of filament.
- V = potential at any radius r , measured from cathode potential.
- V_a = cathode/anode potential-difference.
- V_m = cathode/minimum-surface potential-difference.
- $w = Ve/(k\tau)$ or $(V + V_m)e/(k\tau)$, as specified in the text.
- $w_m = V_me/(k\tau)$
- $w_x = u_x^2/u_r^2$
- $w_y = u_y^2/u_r^2$
- $w_z = u_z^2/u_r^2$
- $w' = w_m - w$
- γ = a constant [equation (2)].
- $\eta = 1 - (r_0^2/r^2)$.
- $\eta' = \eta_m - \eta$
- $\xi = \log r/r_0$ or $\log r/r_m$, as specified in the text.
- ρ = space-charge density.
- τ = absolute temperature of cathode.

(1) INTRODUCTION

According to the qualitative theory of thermionic valves as given in any textbook, the electrons which are emitted from the hot cathode of a valve constitute a total emission current I_0 which depends only on the cathode area and temperature.† If adequate positive potential is applied to the anode, all the emitted electrons are attracted across, and the actual current is equal to I_0 : in this case the current is said to be saturated, or limited by temperature. For smaller applied potentials the current I is found to be less than I_0 , and is said to be limited by space charge. In that case it is supposed that the emitted electrons are met by a retarding potential-gradient, as illustrated in Fig. 1, and that only those pass to the anode which have sufficient initial velocity to overcome the "potential hump" V_m , the remainder being returned to the cathode. It is, of course, an essential part of this theory that the electrons

† Except in the case of abnormally high accelerating fields at the cathode, when the emission is increased by the "Schottky effect."

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† University of Leeds.

should be emitted with distributed velocities, so that the proportion turned back varies continuously with variations of V_m , which in turn depends on the applied anode potential V_a . The surface where $V = -V_m$ is often called the virtual cathode.

Quantitative treatment is based on the work of Langmuir.^{1,2,3} If as a first approximation it can be assumed that d_m and V_m can be neglected in comparison respectively with d_a and V_a and that the electron velocities at the minimum surface (or virtual cathode) can also be neglected, then the famous "three-halves power" law holds, namely

$$I = bV_a^{3/2}$$

where b is a constant depending on the dimensions of the valve. For the case where the electrodes can be taken as infinite parallel planes, the numerical formula is

$$id_a^2 = \frac{1}{9\pi c^2} \left(\frac{m}{2e} \right)^{-1/2} V_a^{3/2} \quad (1)$$

where c is a constant depending upon the units employed

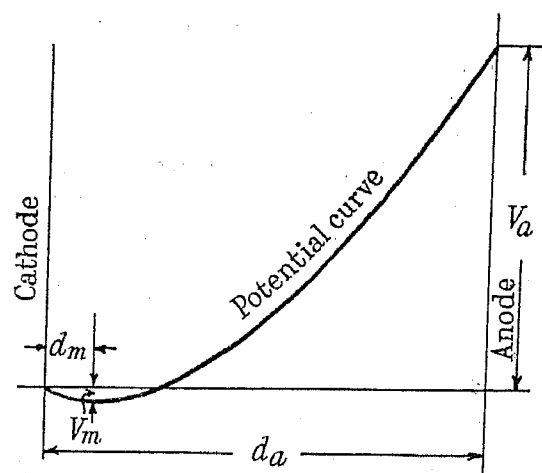


Fig. 1.—Assumed potential distribution in space-charge-limited diode.

and having the value 3.0×10^{10} if c.g.s. electromagnetic units are used, and the other symbols are as defined in the List of Symbols on page 473. In practical units,

$$\frac{1}{9\pi c^2} \left(\frac{m}{2e} \right)^{-1/2} = 2.34 \times 10^{-6} \text{ amp. per volt}^{3/2} \quad (1a)$$

If the electrodes are long cylinders the corresponding formula is

$$id_a^2 = 2.34 \times 10^{-6} \gamma V_a^{3/2} \quad (2)$$

where i is the current per unit anode area and the value of the constant γ lies between 0.83 and 1, as shown in the Table.⁴

In practice the deviations from the three-halves-power law are usually so noticeable that it is an act of some faith to believe that, were it not for the onset of saturation, the law would apply when the voltage was raised high enough. More accurate treatment, however, involves the calculation of V_m and d_m , which in turn involves knowledge of the initial emission velocities, and, more generally, of thermionic theory.

It has long been believed that the high conductivity of metals is due to electrons held within the body of the

solid but otherwise free to move with any potential gradient. At first it was thought that these might have an energy distribution similar to that of the molecules of a perfect gas, and this assumption was the basis of Richardson's original formula for thermionic emission. It is outside the scope of this paper to discuss why in modern theory the distribution of energy among the electrons is taken to be that of a "degenerate" as distinct from a "perfect" gas. It is sufficient to note that the energy distribution of those few which have the highest energies inside the metal is still considered to be the same as if they formed part of a perfect gas, and that it is just those with the highest internal energy which will escape thermionically and constitute the current with which we are concerned. If, further, it is assumed that the nature of the potential barrier which keeps the electrons in the metal exerts no directional discrimination on those which escape, the distribution of initial velocities after escape can also be taken as Maxwellian, i.e. as that of the entirely random motion of the molecules of a gas. Measurements of current made with negative anodes tend to confirm this view.⁵

Theoretical treatment taking account of the distributed initial velocities has been given by Langmuir²

Table

r_a/r_0	γ
1	1.00
2	0.91
5	0.83
10	0.83
30	0.86
700	0.97
2 000	1.00

for the case of infinite parallel planes. Unfortunately, while the planar case is of considerable qualitative interest, the cylindrical diode is the simplest system which can be constructed in practice and therefore the simplest case to which quantitative calculation can be usefully applied. Such calculations are of considerable importance in the study of thermionics and in filament design, and for these reasons the author has thought it worth while to attempt a solution of the cylindrical case taking full account of the distribution of velocities, in order that experimental results may be used as an exact test of the physical phenomena of emission. The results of the solution are given in Sections (2), (3) and (4) of this paper. While the mathematical processes have necessarily been reproduced sufficiently fully for criticism, the details are left to the Appendices.

The problem to be solved is most conveniently tackled by dividing it into three parts: (i) The region of retarding potentials—calculation of voltage and radius of the minimum surface. (ii) The accelerating region—calculation of the volt-ampere characteristic. (iii) The saturated valve.

Assuming the velocity distribution to be Maxwellian, there is no difficulty in establishing a formal expression for the potential V at any radius r of the cylinder as a five-fold integral with respect to dr^2 , du_x , du_y , du_z , where u_x , u_y , u_z are respectively the radial, tangential and axial components of initial velocity at any point of the filament.

Two stages of integration, with respect to du_z and du_x , are simple mathematics; but so far no rigorous method of completing the solution has been found. In this paper the integration is completed by methods yielding approximate solutions, which nevertheless have a known accuracy quite sufficient for all practical purposes.

The symbols used are defined in the List of Symbols (see page 473). The units adopted have to be self-consistent in that w , ξ and η are pure numbers. If V is in volts and τ in degrees K., $e/k = 11\,600$.

It is assumed that the known data are in each case the total emission current, the actual current, the cathode temperature, and the dimensions of the electrode system; it is desired to calculate the voltage. It is found convenient to express the results as relations between the quantities w , ξ and B , defined by

$$B = 2\sqrt{\pi c^2 I r_0} \frac{[m/(2e)]^{\frac{1}{2}}}{(k\tau/e)^{3/2}} \quad (3)$$

In practical units,

$$2\sqrt{\pi c^2} \left(\frac{m}{2e}\right)^{\frac{1}{2}} \left(\frac{k}{e}\right)^{-\frac{3}{2}} = 6.69 \times 10^{10} \text{ (degrees K.)}^{3/2} \text{ per ampere}$$

$$\text{giving} \quad B = \frac{6.69 \times 10^{10} I r_0}{\tau^{3/2}} \quad (3a)$$

Also $B_0 = BI_0/I$, and $B_m = Br_m/r_0$.

(2) SPACE-CHARGE-LIMITED DIODE: REGION OF RETARDING POTENTIALS

The mathematical treatment of this case, which is by a long way the most difficult, is given in Appendix 2. The problem is similar to that of the planar case treated by Langmuir in that at any radius up to the surface of minimum potential there are electrons travelling both ways, some proceeding to the anode to constitute the current I , while others are turned back at some radius before the minimum surface. This last group contributes twice to the space charge at the radius in question, while the first group contributes only once. In a cylindrical system, however, an electron leaving the cathode with purely tangential velocity acquires immediately, by the nature of the case, a radial component, and thus the problem is mathematically much more complicated than the planar case.

The results of the calculation are embodied in Figs. 2 and 3, in which are plotted values of w_m and ξ_m against B for different values of I_0/I , the suffixes m of course referring to the minimum surface as before. The results are correct to within 0.07 of ξ_m and w_m , giving the radius and voltage of the minimum surface correct to within 7 per cent. An example of the use of the curves is given below.

The range of the curves in Figs. 2 and 3 is thought to cover most likely cases, except extremely small values of ξ_m and w_m . For values of $\log_e B$ greater than 1, ξ_m is small and the cylindrical case approximates to the planar, so that Langmuir's solution for the planar case will be found sufficiently accurate here. In any case not covered by the curves, special calculation is easily made by the method given in Appendix 2.

The results given only apply to the case where there is

a minimum surface between cathode and anode: they do not apply to the case where there is a retarding field all the way to the anode. A formula given by Schottky⁶ purports to apply to that case, and probably does not give any very large error in calculation of the current for a given retarding voltage.

(3) SATURATED DIODE

Even when the voltage is sufficient to cause the total emission to flow, there will still be field distortion due to

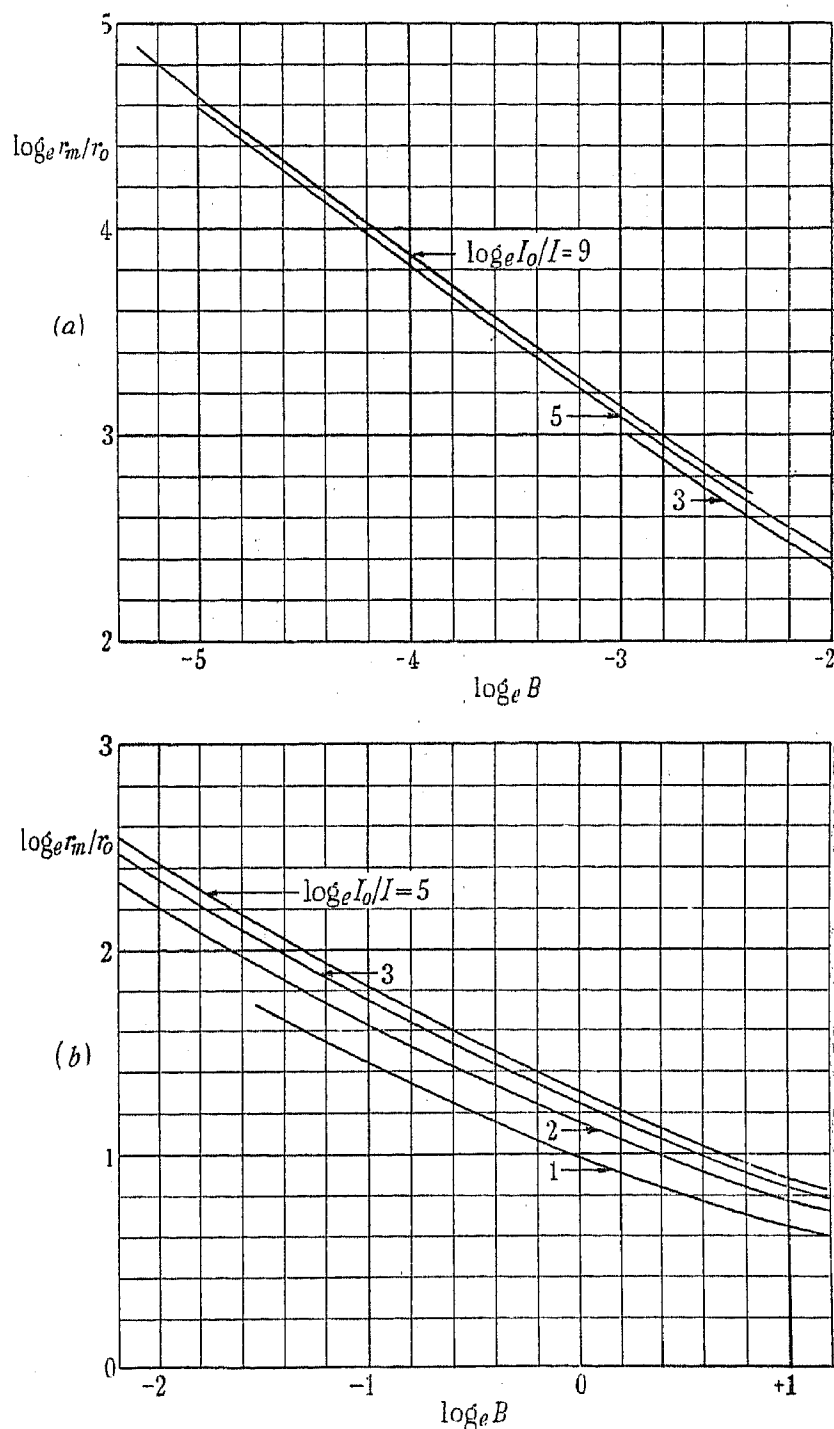


Fig. 2.—Curves for calculating radius of minimum surface.

space charge, and this distortion must be considered in calculating the field strength at the cathode. Langmuir's well-known equation³ deals with the case where the valve has just attained saturation and the cathode field is zero. His solution is obtained by neglecting the initial velocities, and in that case the results can be reduced to a single curve representing Cw in terms of ξ , where C is given by

$$C^{3/2} = \frac{4\sqrt{\pi}}{9B_0} \quad (3b)$$

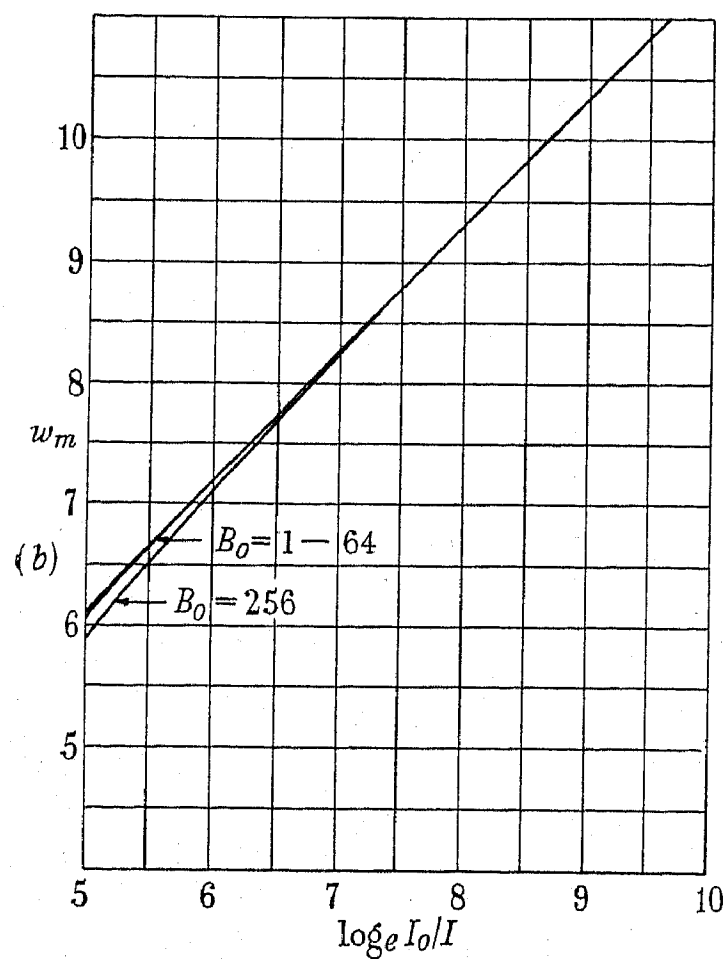
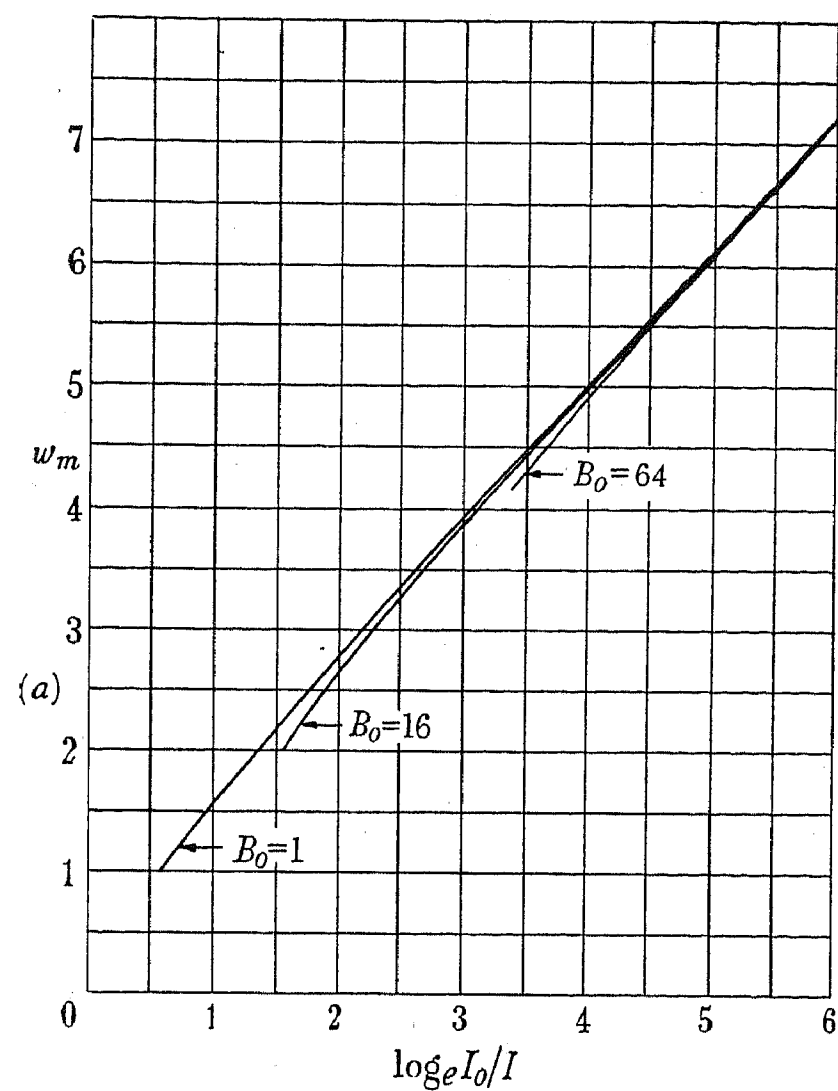


Fig. 3.—Curves for calculating minimum potential.

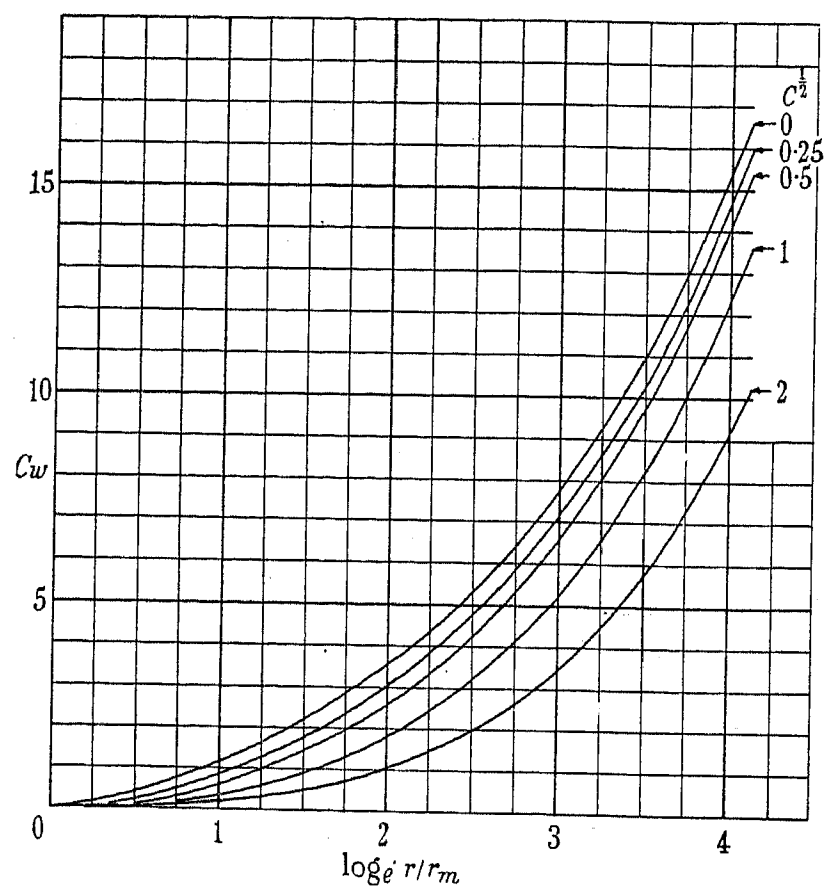


Fig. 4.—Curves for calculating potential of just-saturated diode.

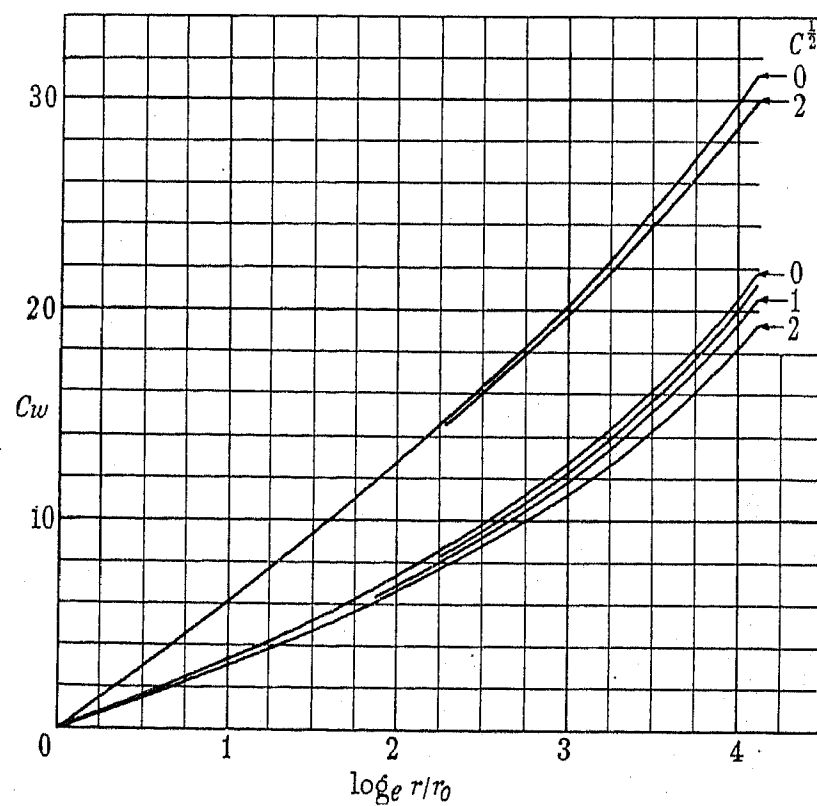


Fig. 5.—Curves for calculating potential of over-saturated diode.

In ampere, centimetre, degree K. units, since from equation (3a)

$$B_0 = \frac{6.69 \times 10^{10} I_0 r_0}{\tau^{3/2}}$$

therefore $C = 5.17 \times 10^{-8} \frac{\tau}{(I_0 r_0 l)^{2/3}} \dots (3c)$

Treatment of the saturated valve taking account of the initial velocities is given in Appendix 3. The results are plotted in Fig. 4. For large currents, i.e. small values of C , the effect of initial velocities is negligible and Langmuir's formula is correct, as given by the curve marked "0" in the Figure. The displacement of the other curves may be taken as approximately proportional to $C^{1/2}$.

For a valve working at maximum output C will probably be small, but for experimental investigations on thin filaments at low temperatures it may be quite appreciable, even at saturation. For example, consider a tungsten filament of 0.2 mm. diameter at 2100° K.; from the figures of Langmuir and Jones,⁷ $I_0/l = 2.46 \times 10^{-4}$ amp. per cm., and thus B_0 works out at 1.71, C at 0.6.

Langmuir's solution applies only to the case where the cathode field is zero. Other solutions of Langmuir's equation have been published for positive cathode fields by Crank, Hartree, Ingham and Sloane;⁸ it remains only to find whether the initial velocities have appreciable effect. Two results are given in Fig. 5, showing that the effect of the velocities decreases as the field increases: it is likely that in any case where the Schottky effect is observed, the Sloane-Hartree results will be quite adequate.

(4) SPACE-CHARGE-LIMITED DIODE: REGION OF ACCELERATING POTENTIALS

In the case of the parallel-plane electrodes the minimum surface behaves exactly as a virtual cathode, in that the electrons leaving it have also a Maxwellian velocity distribution. This is not strictly true of the cylindrical case: nevertheless, it is shown in Appendix 4 that in many cases the error is sufficiently small when the minimum surface is treated as a cathode of radius r_m emitting a current I composed of electrons which are all removed to the anode. The problem therefore reduces to that of considering how far the calculation of the previous Section can be applied. In Fig. 6 a pair of curves is given for each value of C , representing the range of variations with variation of I/I_0 ; where now C , w ,

and ξ are defined respectively as $\left(\frac{4\sqrt{\pi}}{9B_m}\right)^{2/3} \cdot \left(\frac{V + V_m}{k\tau}\right)e$,

and $\log r/r_m$. The lower curve in each case represents the solution for the case $I/I_0 = 1$, as reproduced from Fig. 4, while the upper curve gives the limit for $I/I_0 = 0$. A sufficiently accurate estimate can be made by proportionate interpolation. The two curves merge into the Langmuir solution when C is small; the difference between the two extremes being approximately equivalent to 20 per cent in $C^{1/2}$.

(5) EXAMPLE OF CALCULATION

As an example, consider a valve having a tungsten filament 0.2 mm. dia. and an anode of 5 mm. dia., the

effective axial length being 6 cm. We desire to calculate the potential when $I = 1.0$ milliamp. and $I_0 = 6$ milliamp. Corresponding to $I_0/(lr_0) = 0.1$ amp. per cm², for tungsten $\tau = 2200$ sufficiently nearly. So that, from equation (3),

$$B_0 = 6.5 \quad B = 1.08$$

$$\log_e I_0/I = \log_e 6 = 1.79$$

$$\log_e B = 0.08$$

From Fig. 3(a), $w_m = 2.6$

and from Fig. 2(b), $\xi_m = 1.1$

So that $r_m/r_0 = 3.0$

and $r_m = 0.03$, $B_m = 3.24$

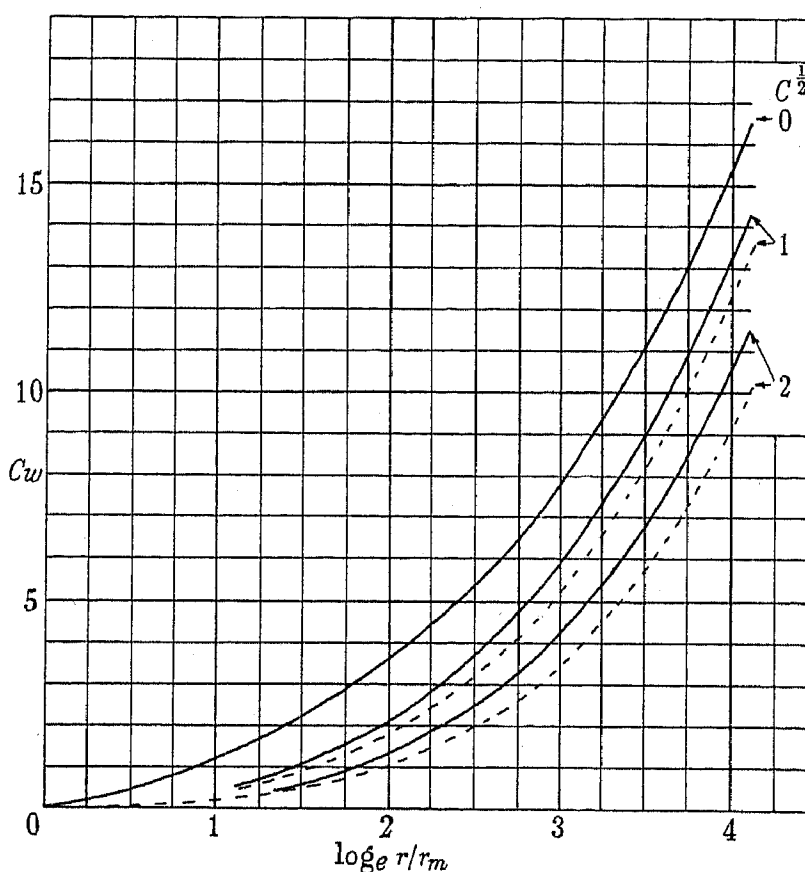


Fig. 6.—Curves for calculating potential of space-charge-limited diode.

For the region of accelerating potentials C , w , ξ are defined as in Section (4) above, and then $C^{3/2} = 0.24$, $C = 0.38$, $C^{1/2} = 0.62$. Also $r_a/r_m = 8.3$, $\log_e r_a/r_m = 2.1$; so that we have, from Fig. 6, $Cw = 3.0$, $w = 7.9$. Thus $w - w_m = Ve/(k\tau) = 5.3$. But $e/(k\tau) = 5.3$, so that $V = 1.0$ volt.

Correction has now to be made for the contact potential-difference between anode and cathode. Suppose, for example, that it be found that the work function of the anode is 0.2 volt higher than that of the cathode; we must add this to the calculated potential to give the value of the applied voltage, 1.2 volt.

It is, incidentally, one of the advantages of the cylindrical system that the contact potential-difference can be directly measured by the magnetron method of Oatley.⁹

(6) REFERENCES

- (1) *Physical Review*, 1913, 2, p. 450.
- (2) *Ibid.*, 1923, 21, p. 419.
- (3) *Ibid.*, 1923, 22, p. 349.
- (4) E. L. E. WHEATCROFT: "Gaseous Electrical Conductors" (Oxford University Press, 1938), chap. 4.
- (5) L. H. GERMER: *Physical Review*, 1925, 25, p. 795.
- (6) *Annalen der Physik*, 1914, 44, p. 1011.
- (7) *General Electric Review*, 1927, 30, p. 310.
- (8) *Proceedings of the Physical Society*, 1939, 5, p. 952.
- (9) *Proceedings of the Royal Society, A*, 1936, 155, p. 218.

APPENDIX 1

Formal Mathematics

(a) Motion of electrons in a cylindrical electric field.

By the nature of the cylindrical case the tangential and axial accelerations are zero, and the radial acceleration (in c.g.s. units) = $(e/m)dV/dr$. From this, by simple integration,

$$u^2 = \frac{2eV}{m} + u_x^2 + \eta u_y^2 \quad (4)$$

where u is the radial velocity and the other symbols have already been defined.

It is convenient to write equation (4) in the form

$$\frac{u^2}{u_r^2} = w + w_x + \eta w_y \quad (4a)$$

where $mu_r^2 = 2k\tau$

With this notation the Maxwellian distribution of initial velocities is defined by the fundamental equation

$$dI = \frac{I_0}{\pi} e^{-(w_x + w_y + w_z)} dw_x \cdot d\sqrt{w_y} \cdot d\sqrt{w_z} \quad (5)$$

where, as before, I_0 is the total current, and dI is that fraction of current due to electrons which had initial velocities in the range

$$(u_x \pm \frac{1}{2}du_x), (u_y \pm \frac{1}{2}du_y), (u_z \pm \frac{1}{2}du_z)$$

(b) Space charge of electrons moving in a cylindrical field.

The contribution to the space-charge density ρ at radius r of the electrons defined by equation (5) is clearly $dI/(2\pi rlu)$, from which

$$d\rho = \frac{I_0}{2\pi^2 rlu_r} (w + w_x + \eta w_y)^{-\frac{1}{2}} e^{-(w_x + w_y + w_z)} dw_x \cdot d\sqrt{w_y} \cdot d\sqrt{w_z} \quad (6)$$

Integrating with respect to w_z between the limits $\pm \infty$, we have

$$d\rho = \frac{I_0}{2\pi^{3/2} rlu_r} (w + w_x + \eta w_y)^{-\frac{1}{2}} e^{-(w_x + w_y)} dw_x d\sqrt{w_y}$$

and so

$$\rho = \frac{I_0}{2\pi^{3/2} rlu_r} S$$

where $S = \iint (w + w_x + \eta w_y)^{-\frac{1}{2}} e^{-(w_x + w_y)} dw_x d\sqrt{w_y} \quad (7)$

(c) The differential equation of potential.

Poisson's equation for the cylindrical case takes the form

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dV}{dr} \right) = 4\pi e^2 \rho$$

from which

$$\frac{d^2 w}{d\xi^2} = \frac{B_0 e^2 S}{\pi} \quad (8)$$

where B_0 has the value previously given [equation (3)].

The problem is to express S in terms of w and ξ , and then to integrate the differential equation for each particular case.

(d) Current of electrons.

The equation for the current is given by integration of

$$dI = \frac{I_0}{\sqrt{\pi}} e^{-(w_x + w_y)} dw_x \cdot d\sqrt{w_y} \quad (9)$$

APPENDIX 2

Retarding Field

(a) Evaluation of space-charge integral.

For the purposes of this Appendix only it is convenient to change the sign of w from that given in the Introduction, so that V now measures the potential *negative* to the cathode. The space-charge integral is then written

$$S = \iint e^{-(w_x + w_y)} (w_x + \eta w_y - w)^{-\frac{1}{2}} dw_x d\sqrt{w_y} \quad (7a)$$

Consider now Fig. 7 for determining the limits of integration of S . At any radius r where the potential is V and η has the value $1 - (r_0^2/r^2)$, we see from equation (4a) that those electrons will fail to arrive for which

$$w_x + \eta w_y < w$$

This limit is shown in the diagram by the straight line $w - w_4$, whose equation is $w_x = w - \eta w_y$. All electrons whose initial velocities give them values of w_x and w_y in the region lying below this limit line contribute nothing to the space charge at r .

As the radius increases, w increases up to a maximum w_m : at the same time w_4 , which is equal to w/η , also varies. w and η are both zero when $r = 0$; w_4 is found to move to the left as w moves up for small values of r . Thus the curve $w_m - \infty$ represents the ultimate envelope traced out by the limit line: it gives the boundary of electrons which are turned back at some radius between r and r_m and so contribute twice to the space charge at r .

Finally, all those whose initial velocities place them in the region above the envelope proceed to the anode, and so contribute once to the space charge at r . These different groups of electrons are indicated by the zones marked "zero," "twice," "once" on the diagram.

It appears at once that it is probably impossible to evaluate the space charge at any radius until the w/ξ relation is found and the ultimate envelope determined; thus the result can only be obtained by successive approximations. Fortunately, it has been found possible to make these converge sufficiently rapidly.

Integration with respect to w_x is achieved by straightforward mathematics and gives (including a factor 2 to

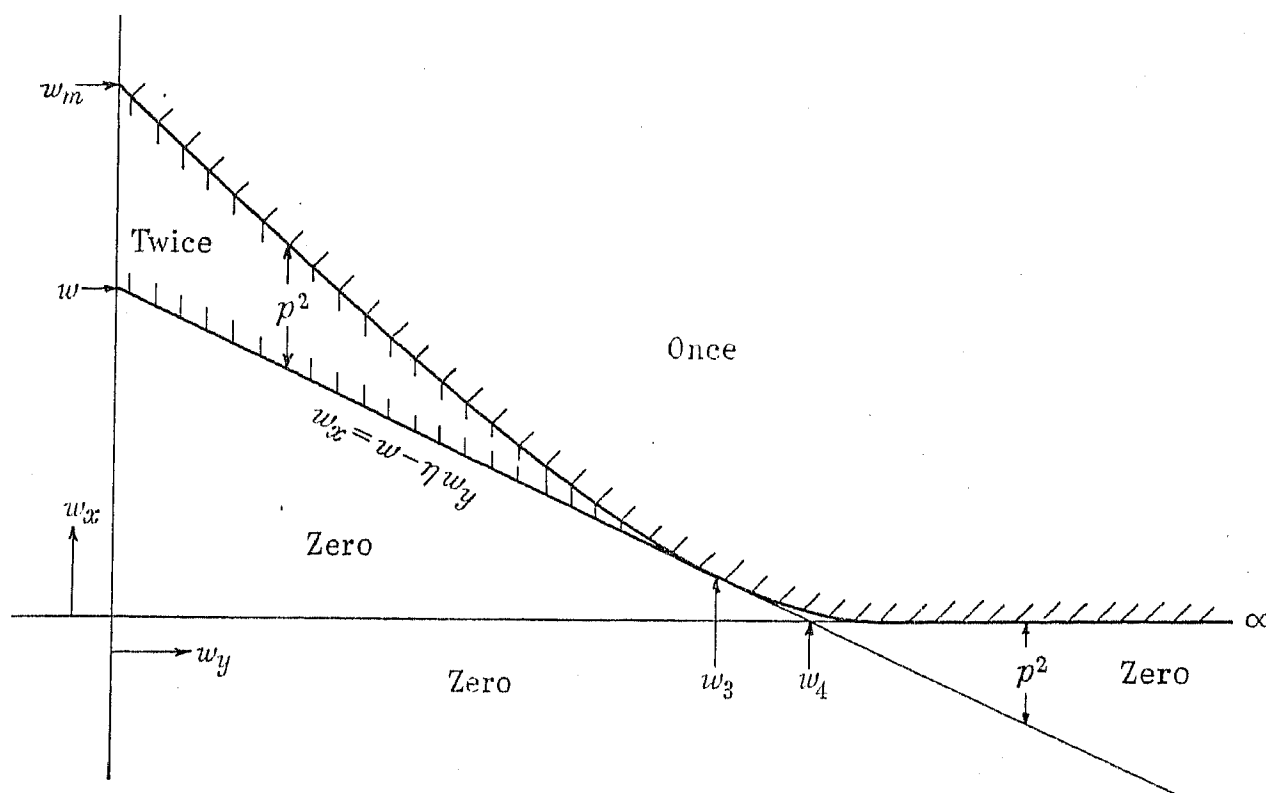


Fig. 7

allow for the fact that w_y will range from $-\infty$ to $+\infty$),

$$S = 2\sqrt{\pi}e^{-w} \left[\int_0^{w_3} (1 + \operatorname{erf} p) e^{(\eta-1)w} d\sqrt{w_y} + \int_{w_3}^{\infty} (1 - \operatorname{erf} p) e^{(\eta-1)w} d\sqrt{w_y} \right] \quad (10)$$

where p^2 is the ordinate difference between the limit line

search for a pair of integrable expressions which respectively over-estimate and under-estimate the true space-charge, in the hope that, when the differential equation (8) is solved, the solutions will be sufficiently near for practical purposes. We are assisted in this by the fact that we may choose arbitrarily one constant of integration (the other being set by the condition that $w = 0$ when $\xi = 0$). For we can decide to choose w_m , the

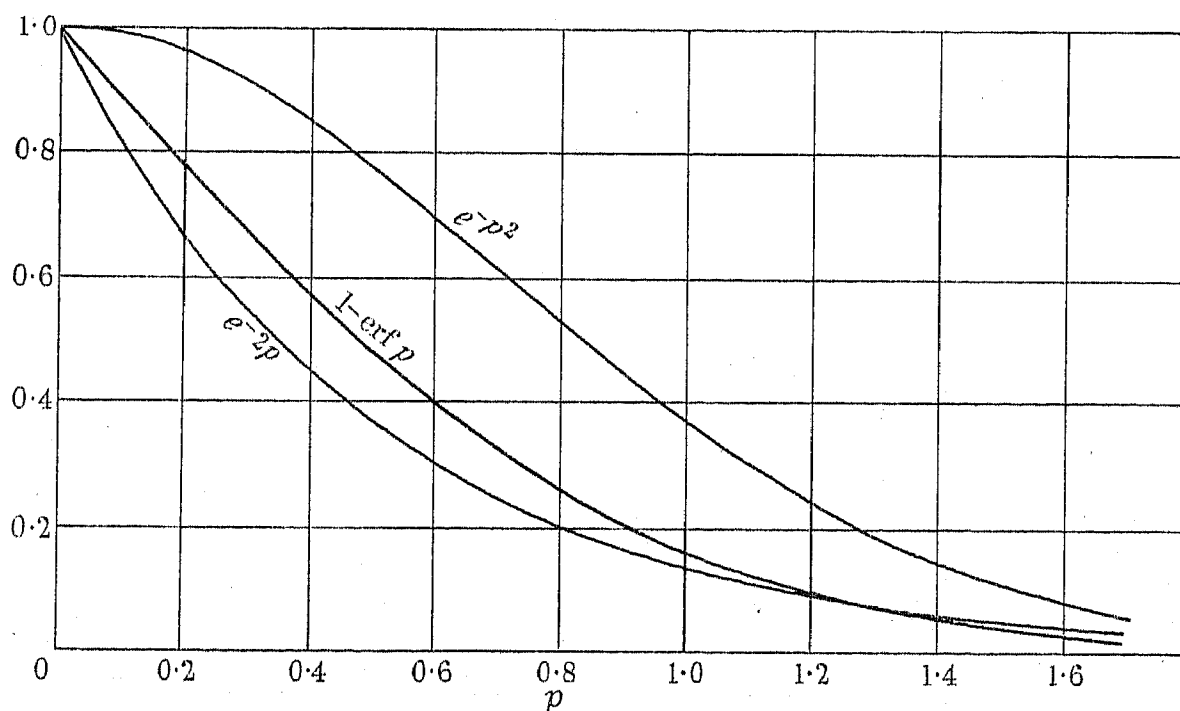


Fig. 8

and the envelope for any value of w_y as indicated in Fig. 7, and $\operatorname{erf} p$ is the error function

$$\frac{2}{\sqrt{\pi}} \int_0^p e^{-t^2} dt$$

whose values can be got from Fig. 8.

From this point on, the only feasible procedure is to

maximum value of w ; this fixes at least one end of the envelope of the limit line, and inspection of the integrand shows that it is the important end.

Fig. 9 shows the basis of a convenient over-estimate of space charge. Imagine the electron velocity distribution to be that shown in Fig. 9 instead of the true distribution shown in Fig. 7. It is clear then that the space charge

deduced from the imagined distribution will be greater than that deduced from Fig. 7. In Fig. 9 then, for the region $w_y < w/\eta$, $p^2 = p_0^2 = w_m - w$; while for the region $w_y > w/\eta$, $p^2 = \eta w_y - w$. But $1 - \operatorname{erfp} < e^{-p^2}$ whatever the value of p (see Fig. 8); so that we have, as a definite over-estimate of S ,

$$S = 2\sqrt{\pi}e^{-w} \left[(1 + \operatorname{erfp}_0) \int_0^{w/\eta} e^{(\eta-1)w_y} d\sqrt{w_y} + \int_{w/\eta}^{\infty} e^{w-w_y} d\sqrt{w_y} \right] \\ = \pi e^{-w} \left\{ (1 + \operatorname{erfp}_0)(1 - \eta)^{-\frac{1}{2}} \operatorname{erf} \sqrt{\left(\frac{w}{\eta} - w\right)} \right. \\ \left. + e^w \left[1 - \operatorname{erf} \sqrt{\left(\frac{w}{\eta}\right)} \right] \right\} \quad \dots \quad (11)$$

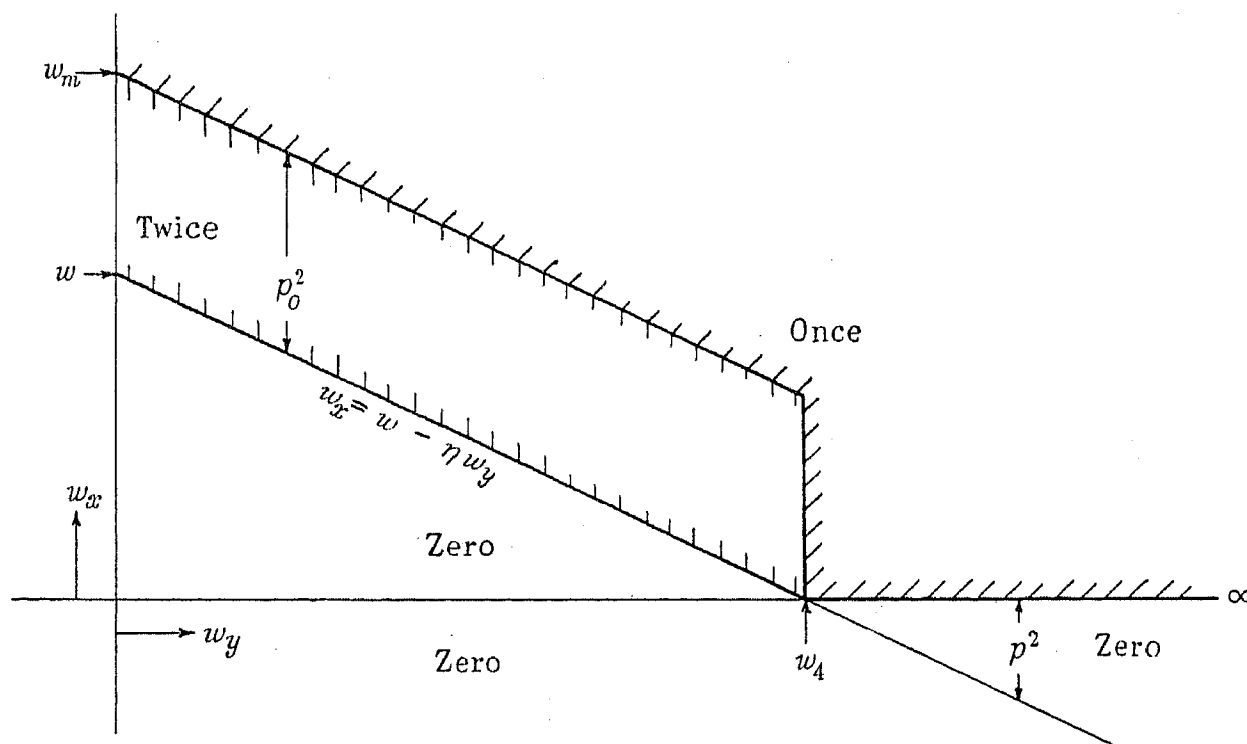


Fig. 9

This expression is sufficiently simple for reasonably rapid calculation.

The differential equation (8) has still to be solved by repeated approximation. This aim is materially assisted by any expression, even if less approximate, which can be integrated directly. We can find such an expression by neglecting the second term in the bracket in (11) above, and assuming that each of the "erf" terms is equal to unity, as will be the case where the arguments are large (see Fig. 8). This leads to the first approximation

$$S = 2\pi e^{\xi-w}$$

since

$$(1 - \eta)^{-\frac{1}{2}} = e^{\xi}$$

giving, from equation (8),

$$\frac{d^2 w}{d\xi^2} = -2B_0 e^{2\xi-w} \quad \dots \quad (12)$$

which is directly integrable, since

$$\frac{d^2 w}{d\xi^2} = \frac{d^2}{d\xi^2} (w - 2\xi)$$

Treatment of the under-estimate is not quite so simple in the first instance, although the integration of equation (8) is in this case facilitated by the over-estimated solution. Imagine first the velocity distribution to be that shown in Fig. 10 instead of the true distribution given in Fig. 7, where w_2 in Fig. 10 lies the left of w_3 in Fig. 7, and all electrons to the right of w_2 are ignored. For the region in Fig. 10 where $w_y < w_2$,

$$p^2 = p_0^2 - (\eta_m - \eta)w_y$$

where, as before, $p_0^2 = w_m - w$.

Making use of the relations

$$1 + \operatorname{erfp} = 2 - (1 - \operatorname{erfp})$$

$$1 - \operatorname{erfp} < e^{-p^2}$$

we have, as a definite under-estimate,

$$S = 2\sqrt{\pi}e^{-w} \left[2e^{(\eta-1)w_y} d\sqrt{w_y} - e^{-p_0^2} \int_0^{w_2} e^{(\eta_m-1)w_y} d\sqrt{w_y} \right] \\ = \pi e^{-w} \left\{ 2(1 - \eta)^{-\frac{1}{2}} \operatorname{erf} \sqrt{[w_2(1 - \eta)]} \right. \\ \left. - e^{-p_0^2} (1 - \eta_m)^{-\frac{1}{2}} \operatorname{erf} \sqrt{[w_2(1 - \eta_m)]} \right\} \quad (13)$$

if $w_2 = (w_m - w)/(\eta_m - \eta)$ or w/η , whichever is the smaller.

The above expression is clearly an under-estimate and is satisfactory in the majority of calculations. In some instances, however, where ξ_m is small, it is found that w_2 decreases rapidly as w approaches w_m , so much so that the under-estimate found by neglecting all to the right of w_2 is too low for practical use, and it is necessary to add additional terms. The following procedure has then been found satisfactory.

Obtain a solution after the manner outlined above, making use of the over-estimate, and use this solution to plot the envelope of the limit line. By inspection draw a curve, shown dotted in Fig. 10, which will everywhere lie above the envelope, and such that $p_m = aw_y$ where

a is a constant. Then it will be seen that $p < p_m$ over the region where $w_2 < w_y < w/\eta$, and so $(1 - \operatorname{erf} p) > (1 - \operatorname{erf} p_m)$. If then in this region we are content to consider only those electrons which contribute

$dw/d\xi = 0$ where $w = w_m$. As stated above, such a relation can be based on the solution of equation (12). Se^ξ is then calculated as a function of w , and equation (8) integrated graphically with respect to w under the

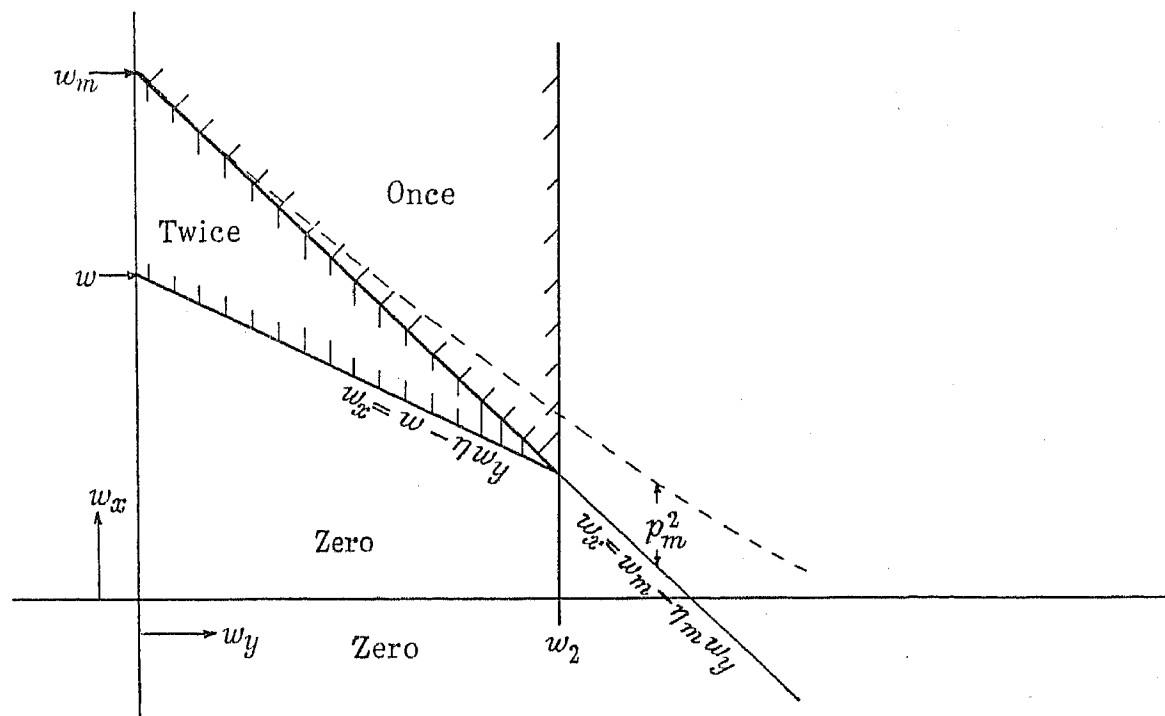


Fig. 10

once to the space charge, which is clearly still an underestimate of the true condition, we have to add to the expression for S a term

$$2\sqrt{\pi}e^{-w} \int_{w_2}^{w/\eta} (1 - \operatorname{erf} p) e^{(\eta-1)w_y} d\sqrt{w_y} \quad (14)$$

which may itself be under-estimated at

$$2\sqrt{\pi}e^{-w} \int_{w_2}^{w/\eta} (1 - \operatorname{erf} p_m) e^{(\eta-1)w_y} d\sqrt{w_y}$$

Now it can be shown that, over the relevant range of p ,

$$\int (1 - \operatorname{erf} p) d\sqrt{p} > \int e^{-2p} d\sqrt{p}$$

so we may further under-estimate at

$$\begin{aligned} & 2\sqrt{\pi}e^{-w} \int_{w_2}^{w/\eta} e^{(\eta-1-2a)w_y} d\sqrt{w_y} \\ &= \pi e^{-w} (1 - \eta + 2a)^{-1/2} \left\{ \operatorname{erf} \sqrt{[(1 - \eta + 2a)w/\eta]} \right. \\ & \quad \left. - \operatorname{erf} \sqrt{[(1 - \eta + 2a)w_2]} \right\} \quad (15) \end{aligned}$$

This additional term in the expression S vanishes, of course, if $w_2 > w/\eta$, and in any case is unimportant except as w approaches w_m .

(b) Solution of the differential equation.

The equation to be solved is now

$$\frac{d^2 w}{d\xi^2} = \frac{B_0}{\pi} e^S \quad (8)$$

where S has alternatively the values given in expressions (11) and (13). The method which has given satisfactory results is to begin with an assumed relation of ξ to w satisfying the conditions $\xi = 0$ when $w = 0$, and

condition that $dw/d\xi = 0$ when $w = w_m$. From this integration of $(d\xi/dw)dw$ yields a second value of ξ .

It is, however, necessary to ensure that the successive values of ξ converge. Consider the curves shown in Fig. 11, where ξ is the true function satisfying equa-

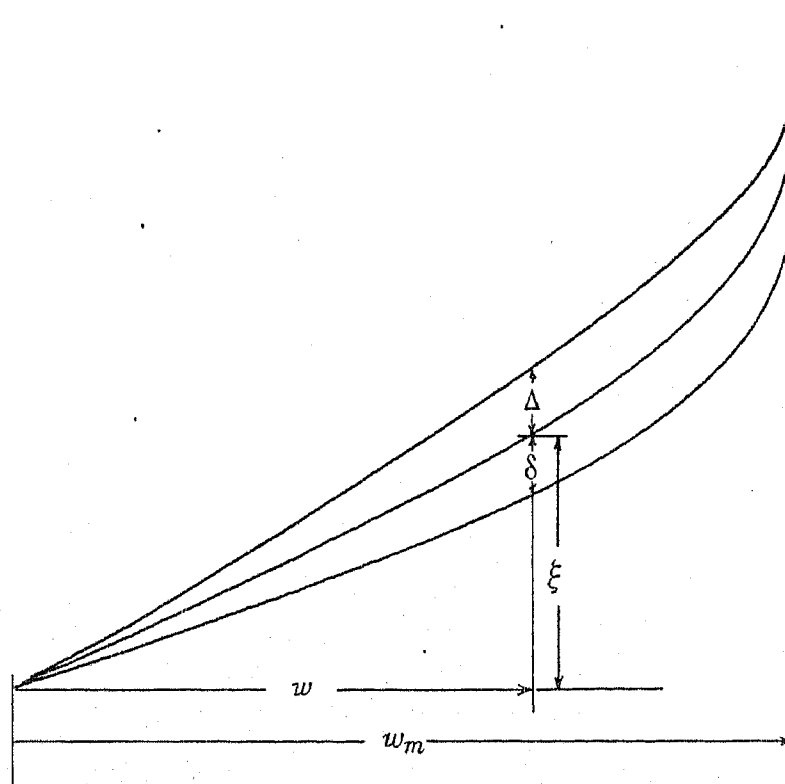


Fig. 11

tion (8) and $(\xi - \delta)$ an approximation. Experience shows that S does not change very greatly with small variations of ξ , so that we may for the moment consider it constant. Suppose now that the process of graphical integration described above based on the relation

$(\xi - \delta)$ yields a result $(\xi + \Delta)$ as shown in the Figure. Then we have

$$\frac{d^2w}{d(\xi + \Delta)^2} = \frac{B_0}{\pi} S e^{\xi - \delta}$$

and

$$\frac{d^2w}{d\xi^2} = \frac{B_0}{\pi} S e^{\xi}$$

so that, if δ and Δ are both small,

$$1 - \frac{2\Delta}{\xi} = 1 - \delta$$

$$\frac{\Delta + \delta}{\delta} = 1 + \frac{\xi}{2}$$

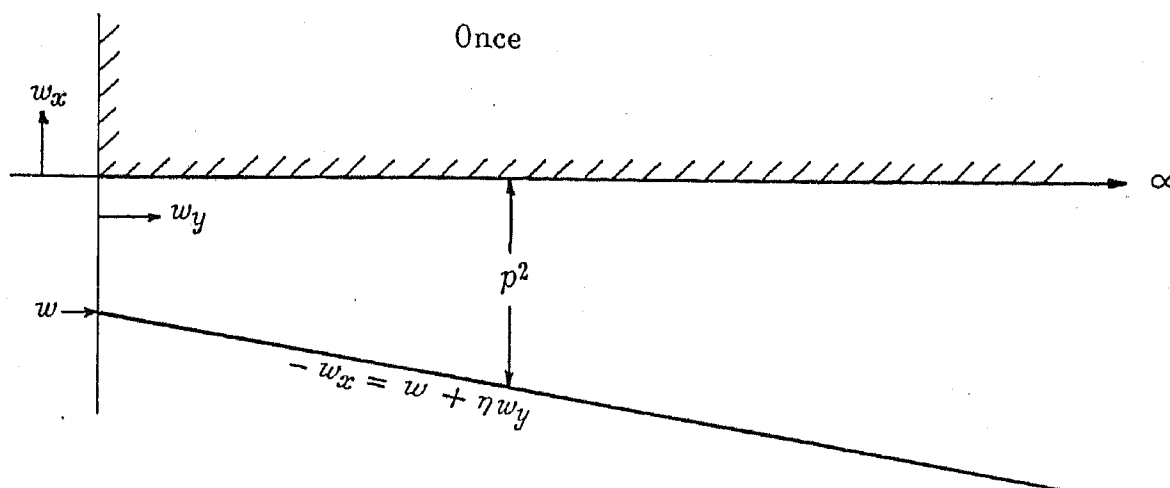


Fig. 12

This enables a second approximation for ξ to be interpolated between the two curves $(\xi - \delta)$ and $(\xi + \Delta)$, and in practice the successive approximations converge quite rapidly.

(c) Calculation of the current.

When the ξ/w relation has been found for any given value of w_m and the limit diagram drawn, the data are available for the equation of current

$$I = \frac{I_0}{\sqrt{\pi}} \iint e^{-(w_x + w_y)} dw_x d\sqrt{w_y} = \frac{2I_0}{\sqrt{\pi}} \int_0^\infty e^{-(w_x + w_y)} d\sqrt{w_y} \quad (9a)$$

where w_x has the value given by the envelope of the limit line, and the factor 2 is included to allow for both senses of w_y .

The result is easily obtained by graphical integration. It appears that in those cases where $\xi_m > 1$ no appreciable error is involved in taking the envelope as consisting of the straight line $w_x = w_m - \eta_m w_y$ down to the point where this line cuts the w_y axis, and thereafter following that axis; this yields Schottky's formula

$$I = I_0 e^{-w_m} \left\{ (1 - \eta_m)^{-\frac{1}{2}} \operatorname{erf} \left(\frac{w_m}{\eta_m} - w_m \right) + e^{w_m} \left[1 - \operatorname{erf} \sqrt{\left(\frac{w_m}{\eta_m} \right)} \right] \right\} \quad (16)$$

Even with ξ_m down to 0.6 the error involved in taking Schottky's formula is not more than 8 per cent.

APPENDIX 3

Saturated Valve

(a) The space-charge integral.

In the case of a saturated valve the current is the total emission of electrons having a velocity distribution corresponding to equation (5). The equation of the space-charge integral is now

$$2\sqrt{\pi} e^{+w} \int_0^\infty (1 - \operatorname{erf} p) e^{(\eta-1)w_y} d\sqrt{w_y} \quad (17)$$

where p^2 is now given by the limit diagram of Fig. 12, in which positive w now corresponds to positive potential from the cathode. From the diagram, $p^2 = w + \eta w_y$.

It can be shown that with sufficient accuracy for our purpose this integral can be expressed in general terms as follows:—

$$\int_0^\infty e^{(w+\eta w_y)} [1 - \operatorname{erf} \sqrt{(w + \eta w_y)}] e^{-w_y} d\sqrt{w_y} = \frac{\sqrt{\pi}}{2} f(w + 0.3\eta) \quad (18)$$

where $f(t)$ stands for $e^t(1 - \operatorname{erf} \sqrt{t})$.

The error in this empirical expression is never more than 6 per cent for any values of w or η , and rapidly vanishes as w becomes large.

The differential equation (8) then takes the form

$$\frac{d^2w}{d\xi^2} = B_0 e^{\xi} f(w + 0.3\eta) \quad (19)$$

Equation (19) reduces to that of Langmuir if the initial velocities are neglected. For this neglect is equivalent to making τ approach zero: η then becomes negligible compared with w , as w approaches infinity. With w large, $f(w)$ becomes $(\pi w)^{-\frac{1}{2}}$, and the equation becomes

$$\frac{d^2w}{d\xi^2} = \frac{B_0}{\sqrt{\pi}} e^{\xi} w^{-\frac{1}{2}}$$

The term $k\tau/e$ cancels from the equation, giving

$$e^{-\xi} \frac{d^2V}{d\xi^2} = \frac{2c^2 I_0 r_0 [m/(2e)]^{\frac{1}{2}}}{l V^{\frac{1}{2}}} \quad (20)$$

which is Langmuir's equation in our symbols.

(b) Solution of the potential equation.

Langmuir's integration applies only to the initial condition $dw/d\xi = 0$, corresponding to the case of a valve which has just attained saturation. Appendix 4 discusses how far it can also be applied to the case of a

venient, however, in searching for a more general solution to consider how far the minimum surface can be treated as a virtual cathode. For this purpose Fig. 13 is redrawn in Fig. 14 with a new origin at w_m , and the line whose equation was originally $w_x = w_m - \eta_m w_y$ as the new axis.

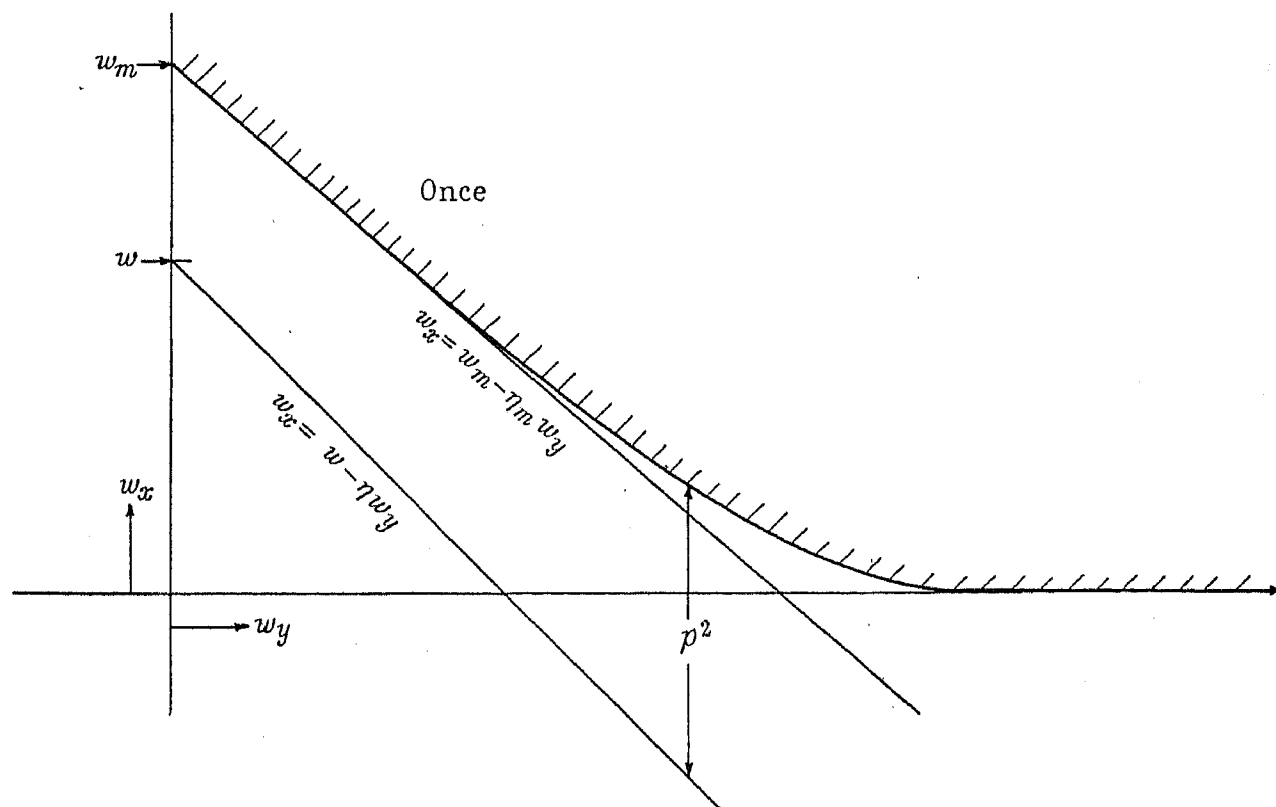


Fig. 13

valve operating in the region of space-charge limitation, the surface of minimum potential being reckoned as a virtual cathode.

The Sloan-Hartree solutions quoted above⁸ may be used for the cases of positive initial values of $dw/d\xi$ where the initial velocities can be neglected; alternatively, by the process of integration by steps and successive approximation, either equation (19) or equation (20) can be easily solved for any initial condition. Briefly, the method is to divide the range of ξ into a series of steps, and to obtain a rapidly converging solution by graphical integration of each, $d^2w/d\xi^2$ being extrapolated from one step to the next.

The solution of equation (20) [but not of equation (19)] can be made independent of the value of B by making the independent variable Cw , where, as already explained,

$$C = \left(\frac{4\sqrt{\pi}}{9B_0} \right)^{\frac{1}{2}} \quad (3b)$$

APPENDIX 4 Accelerating Field

The problem of calculating the potential characteristic for the region beyond the minimum surface can be treated by the same methods as those adopted for the retarding field, being in fact somewhat simpler in that the envelope of the limit line is now known. The point w in Fig. 7 is now receding from w_m , carrying down with it the limit line as shown in Fig. 13. Eventually w passes through zero and changes sign, to correspond then with positive potential relative to the cathode. It is con-

Fig. 14 may then be compared with Fig. 12, which represents a true cathode.

From Fig. 13 we have

$$S = 2\sqrt{\pi}e^{-w} \int_0^\infty (1 - \operatorname{erf} p) e^{(\eta-1)w_y} d\sqrt{w_y} \quad (21)$$

$$I = \frac{2}{\sqrt{\pi}} I_0 \int_0^\infty e^{-w-p^2+(\eta-1)w_y} d\sqrt{w_y} \quad (22)$$

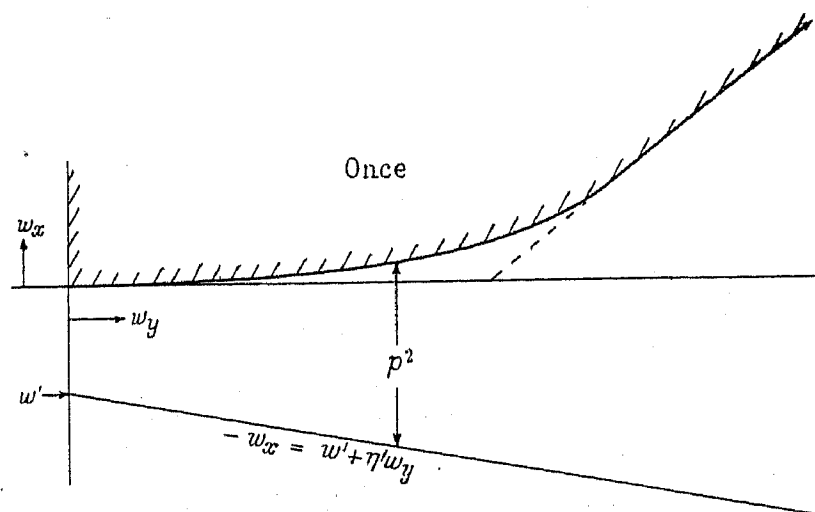


Fig. 14

For an over-estimate of space charge we may note that, for $p > p_0$,

$$1 - \operatorname{erf} p < (1 - \operatorname{erf} p_0) e^{p_0^2 - p^2}$$

If then $p_0 = w' = w_m - w = (V + V_m)e/(k\tau)$,

this approximation gives

$$S = \frac{\pi I}{I_0} f(p_0^2)$$

the function f being defined as before [equation (18)]; and

$$\frac{d^2 w'}{d\xi^2} = B_m e^{\xi} f(w') \quad \dots \quad (23)$$

where $\xi = \log r/r_m$ as in Section (4) of the paper.

In fact, it turns out from the shape of the envelope as

found from the solutions of Appendix 1 that equation (23) gives a close approximation when I_0/I is large, while of course when $I_0/I = 1$ the minimum surface coincides with the cathode, and equation (19) holds. The two solutions thus represent the range of variation; they are compared in Fig. 6, where the lower curve of each pair represents the solution for a true cathode. The two curves merge into the Langmuir solution when C is small; the difference between the two solutions is equivalent to approximately 20 per cent in $C^{\frac{1}{2}}$, C and w of course being defined as in Section (4) of the paper.

DISCUSSION ON

"THE ELECTRIC AND MAGNETIC FIELDS OF A LINEAR RADIATOR CARRYING A PROGRESSIVE WAVE"*

Mr. L. Lewin (*communicated*): In his paper the author, using as auxiliary mathematical quantities the vector and scalar potentials, derives expressions for the field strength in the vicinity of a radiating wire. Towards the end of the paper these expressions are used to calculate the radiation resistance of a wire of length $2l$, and the result is found to be $30F(8\pi l/\lambda)$ ohms,† the same as that of a standing-wave radiator of the same length, assuming that the latter is composed of an integral number of half-waves. As the far-field polar diagram of a standing-wave radiator is different from that of the same radiator carrying a progressive current-wave, the above result is somewhat unexpected.

The radiation resistance of a progressive-wave radiator was re-calculated by means of the Hertzian vector method, and checked independently by integrating the Poynting vector over an infinite spherical surface enclosing the radiator. The resulting value differs from the value previously stated, and the cause of the difference appears to be that, in his paper, the author has used only that part of the electric field produced by the portion of the scalar potential arising from the distribution of electric charge along the wire. As he explains, the scalar potential is formed of three parts, ψ_0 due to the distribution of electric charge along the wire, and ψ_1 and ψ_2 due to terminating charges necessary to furnish and absorb the currents at the ends of the wire. If a closed circuit is under consideration, adjacent ends of component radiators will have associated with them equal and opposite charges, so that the field-strength terms from these will

not appear in the final formulation of the total field strength produced by the system at a point. In calculating the power radiated from a part of a complete circuit, it is therefore unnecessary to consider the effect of these charges. The radiated power as thus calculated will be the sum of the self-radiation (the power radiated due to the influence of the radiator's own field on itself) and the power radiated due to the mutual influence of the rest of the circuit. If only the self-radiation of a conductor forming a part of a system is to be calculated, this means that the influence of the rest of the circuit is not to be considered. Therefore it is incorrect to ignore the terms arising from the terminating charges. Their disappearance from the expression for the total power radiated by the conductor, when the rest of the circuit is considered, is due to the presence of charges of opposite sign at the ends of, and associated with, adjacent radiators. When the effect of these charges is considered, the value of the self-radiation resistance is found to be

$$60 \left[F\left(\frac{8\pi l}{\lambda}\right) - 1 + \frac{\sin 8\pi l/\lambda}{8\pi l/\lambda} \right] \text{ ohms}$$

Taking $l = \frac{1}{2}\lambda$, this formula gives a value of 86 ohms, as compared with 73 ohms for a standing-wave radiator of the same length.

It should be pointed out that it is unnecessary to assume terminating charges when the Poynting vector and Hertzian vector methods are used.

Mr. F. M. Colebrook (*in reply*): I am grateful to Mr. Lewin for pointing out that in my calculation of the radiation resistance of a progressive-wave radiator it is tacitly assumed that the radiator is part of a closed circuit, as of course it will necessarily be in any practical case. This should have been made clear in the text.

* Paper by Mr. F. M. COLEBROOK (see page 169).

† $F(x) = \int_0^x \frac{1 - \cos x}{x} dx$

THE INFLUENCE OF VARIOUS FACTORS UPON THE LEAKAGE REACTANCE OF TRANSFORMERS*

By A. LANGLEY MORRIS, Associate Member.†

(Paper first received 29th January, 1938, in revised form 25th April, and in final form 21st October, 1939.)

SUMMARY

This paper investigates the leakage reactance of transformers by means of Roth's potential-vector method of analysis. The potential vector is divided into three components. The first component gives rise to the normal reactance as calculated by Kapp's equation; this is termed the "axial reactance." The second, which is responsible for additional leakage reactance, is termed the "radial component." The third, which does not lend itself to easy mathematical treatment, is shown to modify the axial term, giving a closer degree of approximation by its inclusion.

In order to enable the total leakage reactance of various winding arrangements to be calculated, three Tables are provided. Thus it is possible to allow for the effects of cooling ducts, tapplings, and end-turn reinforcement. In Appendix I a comparison is made between the calculated and tested values of the leakage reactance of two commercial transformers having non-uniform distribution of ampere-turns.

INTRODUCTION

A rigorous analysis of the leakage reactance of transformers is a formidable undertaking if the effect of every factor is to be considered. Even if a solution were obtained, the derivation of numerical values would be extremely laborious. On the other hand the solution of a simplified representation of a transformer is not difficult and yields numerical results without recourse to involved calculations.

The original expression for the leakage reactance [see equation (10)] is due to Kapp,¹ and represents a simplified analysis of the problem of transformer reactance. Errors will, however, occur whenever the basic assumptions cease to be valid. One of the main assumptions made is that of uniform ampere-turn distribution throughout the transformer windings. The provision of tapplings, cooling ducts, and inter-turn reinforcement, gives an asymmetrical ampere-turn distribution, and the indiscriminate employment of Kapp's expression may therefore lead to large errors.

An ideal method of analysing transformer leakage-reactance problems is provided by the elegant potential-vector method of Roth.^{2,3,4} The expressions obtained by means of Roth's analysis do not, however, always lend themselves to easy numerical computation. The aim of this paper is to obtain expressions which take account of the various factors influencing the leakage reactance. By means of Roth's analysis it has been

possible to extend Kapp's basic expression to allow for non-uniform ampere-turn distribution.

GENERAL SOLUTION OF LEAKAGE FLUX PROBLEMS

In the original analysis of Kapp¹ and of Roth^{2,3,4} the problem was regarded as two-dimensional. Circular windings then have to be represented by long parallel bars having a length equal to the mean turn of the primary and secondary. In Roth's treatment, which is the one upon which this paper is based, the windings are assumed to be bounded on all four sides by iron

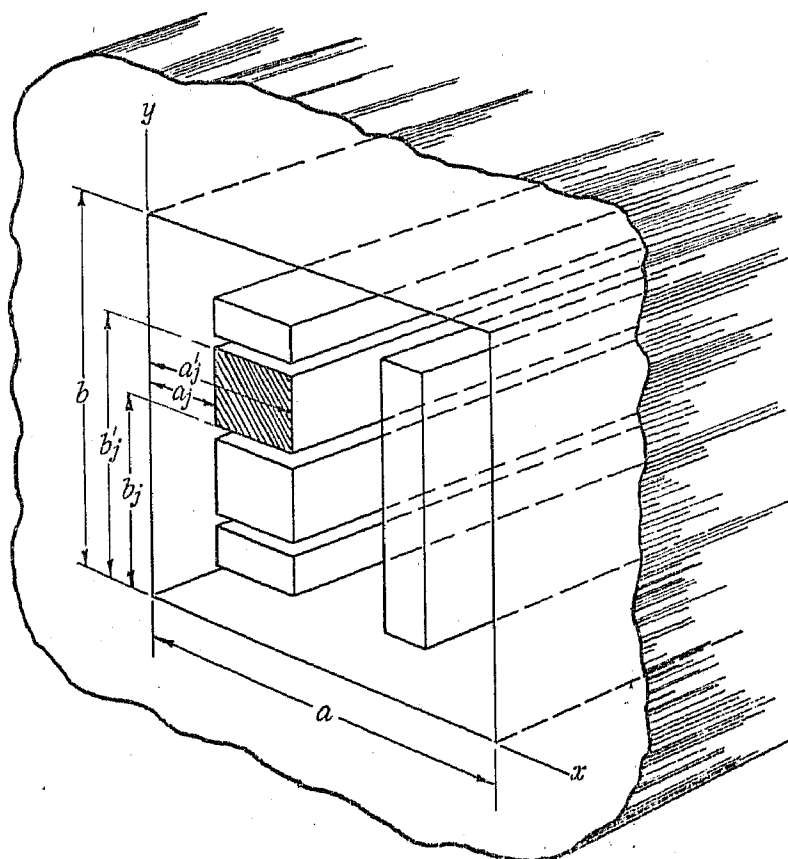


Fig. 1.—Fundamental conception of a transformer.

having infinite permeability. Such a condition is the same as that of windings contained in a closed slot in an iron core (see Fig. 1). Heiles⁵ has shown that in actual practice this closed-slot condition is approximately realized.

Roth⁶ has recently analysed the case of cylindrical windings, the solution involving Bessel-Fourier functions. It was decided, in the interests of general practical application, to avoid consideration of the three-dimensional aspects of the problem of transformer leakage reactance, and only the two-dimensional solution has, therefore, been attempted.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† Messrs. Johnson and Phillips, Ltd.

Employing Roth's notation, the potential vector of the system, as shown in Fig. 1, is

$$\Pi = \sum_{i=1}^{\infty} \sum_{k=1}^{\infty} A_{ik} \cdot \cos m_i x \cdot \cos n_k y \quad (1)$$

where

$$m_i = (i - 1) \frac{\pi}{a},$$

$$n_k = (k - 1) \frac{\pi}{b},$$

Equation (5) defines the exact magnetic conditions existing within the boundaries "a" and "b" of Fig. 1. It is thus possible to determine the leakage flux for any arrangement of conductors existing inside the slot.

The meaning of these potential vectors will be better appreciated upon reference to the diagrams of the flux leakage shown in Fig. 2.

Fig. 2(a) may represent a transformer winding bounded on all four sides by an iron core. The longer winding can be the primary and the other one the secondary.

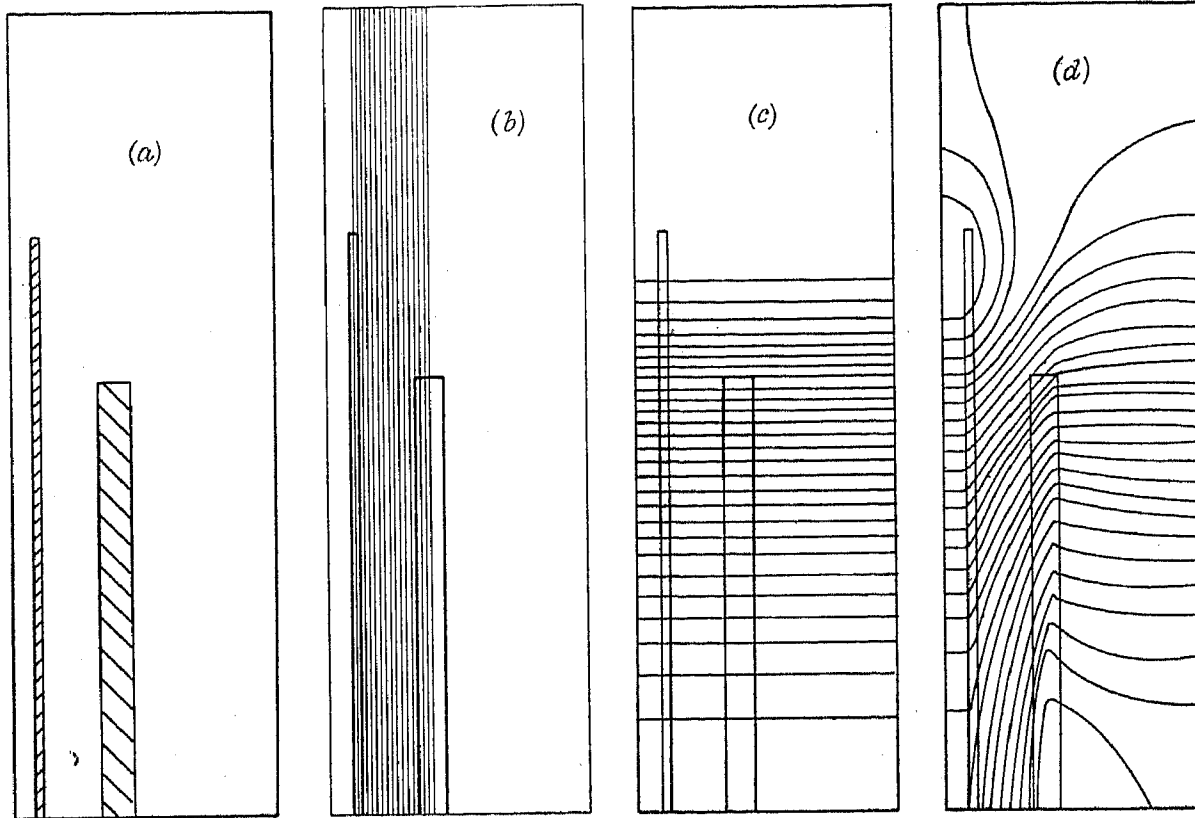


Fig. 2

- (a) Disposition of conductors.
(b) Axial flux due to π_1 .
(c) Radial flux due to π_2 .
(d) Flux due to $\pi_1 + \pi_2 + \pi_3$.

and

$$A_{ik} = \frac{16\pi}{10ab} \sum_{j=1}^{j=q} \frac{I_j N_j (\sin m_i a'_j - \sin m_i a_j) (\sin n_k b'_j - \sin n_k b_j)}{(a'_j - a_j)(b'_j - b_j) \cdot m_i n_k (m_i^2 + n_k^2)}$$

i and k are positive integers, $I_j N_j$ are the ampere-turns of the conductor of order j , and q is the total number of conductors in the system.

Equation (1) may be split up into three parts:—

$$\pi_1 = \frac{8\pi}{10ab} \sum_{j=1}^{j=q} \frac{I_j N_j}{a'_j - a_j} \sum_{i=2}^{\infty} (\sin m_i a'_j - \sin m_i a_j) \frac{\cos m_i x}{m_i^3} \quad (2)$$

$$\pi_2 = \frac{8\pi}{10ab} \sum_{j=1}^{j=q} \frac{I_j N_j}{b'_j - b_j} \sum_{k=2}^{\infty} (\sin n_k b'_j - \sin n_k b_j) \frac{\cos n_k y}{n_k^3} \quad (3)$$

$$\pi_3 = \frac{16\pi}{10ab} \sum_{j=1}^{j=q} \frac{I_j N_j}{(a'_j - a_j)(b'_j - b_j)} \sum_{i=2}^{\infty} \frac{\sin m_i a'_j - \sin m_i a_j}{m_i^2 + n_k^2} \cdot \frac{\cos m_i x}{m_i} \times \sum_{k=2}^{\infty} (\sin n_k b'_j - \sin n_k b_j) \frac{\cos n_k y}{n_k} \quad (4)$$

where

$$\Pi = \pi_1 + \pi_2 + \pi_3 \quad (5)$$

The leakage flux due to π_1 is depicted in Fig. 2(b), and it is an axial leakage flux.

Fig. 2(c) shows the leakage flux due to π_2 . This flux is at right angles to that of π_1 , and is produced by the unequal axial ampere-turn distribution in the windings.

Fig. 2(d) represents the actual leakage flux Π and is the combined effect of π_1 , π_2 and π_3 . The major effect of π_3 is to modify the flux distribution in the region between the upper boundary and the top of the windings, so that few flux lines leave the upper boundary.

The flux density B of the leakage flux is obtained by partial differentiation of the potential vectors.

The axial component

$$B_y = \frac{\partial \Pi}{\partial x}$$

and the radial component

$$B_x = \frac{\partial \Pi}{\partial y}$$

Roth and Kouskoff⁷ have shown that in certain cases the infinite series involved in these equations can be reduced to finite terms.

Thus

$$\sum_{i=2}^{\infty} \frac{\sin m_i a_j \sin m_i x}{m_i^2} = \frac{x}{2}(a - a_j) \quad (6a)$$

for $x < a_j$

and $= \frac{1}{2}a_j(a - x) \quad (6b)$
for $x > a_j$

and

$$\sum_{i=2}^{\infty} \frac{\sin m_i a_j \cos m_i x}{m_i(m_i^2 + n_k^2)} = \frac{a}{2n_k^2} \left[\frac{a - a_j}{a} - \frac{\cosh n_k x \cdot \sinh n_k(a - a_j)}{\sinh n_k a} \right] \quad (7a)$$

for $x < a_j$

and $= \frac{a}{2n_k^2} \left[\frac{\sinh n_k a_j \cosh n_k(a - x)}{\sinh n_k a} - \frac{a_j}{a} \right] \quad (7b)$
for $x > a_j$

It will be appreciated that b, b', y , etc., may be substituted for a, a', x , etc., in the above expressions.

By the aid of the above equations $\partial\pi_1/\partial x$ and $\partial\pi_2/\partial y$ are reduced to finite terms, the former giving the axial flux density and the latter the radial flux density. On the other hand π_3 , however, may only be reduced to a finite term plus a single infinite series.

The percentage leakage reactance is obtained from the expressions for the flux density, and may be expressed as two separate components as far as π_1 and π_2 are concerned, one being the axial and the other the radial reactance.

Thus the former

$$X_y = \frac{10^{-5}\omega r}{4\pi VI} \iint B_y^2 dy dx \quad (8)$$

and the latter

$$X_x = \frac{10^{-5}\omega r}{4\pi VI} \iint B_x^2 dx dy \quad (9)$$

where $X_y = \% \text{ axial reactance,}$
 $X_x = \% \text{ radial reactance,}$
 $\omega = 2\pi \times \text{frequency,}$
 $VI = \text{volt-amperes of the winding,}$
 $r = \text{mean turn of the windings.}$

THE REACTANCE AND FLUX DENSITY DUE TO π_1

When equation (2) is differentiated with respect to x , the expression obtained gives the axial flux density B_y . In dealing with the effects of leakage flux in transformers, this particular component is usually the one considered. It is the main component of the total leakage flux.

The leakage reactance calculated by Kapp's expression¹ is due to this axial flux, and may therefore be termed the axial leakage reactance.

The expression for this reactance is:—

$$X_y = \frac{4\pi}{10^7} \cdot \frac{\omega IN^2}{V} \cdot \frac{r}{b} \left(\frac{\Delta_p}{3} + \frac{\Delta_s}{3} + \delta \right) \quad (10)$$

where $N = \text{number of turns in the primary winding,}$
 $r = \text{length of mean turns of primary and secondary windings,}$
 $b = \text{axial height of winding,}$
 $\Delta_p, \Delta_s = \text{radial width of the primary and secondary windings respectively,}$
 $\delta = \text{radial spacing between the primary and secondary windings,}$

all dimensions being in centimetres.

A similar expression may be obtained from equation (2), in the manner already described, provided the axial boundary is made to coincide with the extremities of the windings.

The axial component is modified by the introduction of axial cooling ducts and also by interleaving the windings. It is necessary, therefore, to modify equation (10) to take account of these conditions.

Axial Ducts in the Windings

Consider a winding, which may be either the primary or the secondary, consisting of a number of coils q with $(q - 1)$ axial ducts; then the axial flux density over the p th coil is given by

$$B_y = -\frac{4\pi}{10} \cdot \frac{IN}{b} \left[\frac{z_p x}{\Delta_p} + \sum_{p=1}^{q-1} z - \frac{z_p}{\Delta_p} \sum_{p=1}^{q-1} (\Delta + \delta) \right] \quad (11)$$

and over the p th duct by

$$B_y = -\frac{4\pi}{10} \frac{IN}{b} \sum_{p=1}^q (z) \quad (12)$$

where $\Delta_p = \text{radial width of the } p\text{th coil,}$
 $\delta_p = \text{radial width of the } p\text{th duct,}$
 $z = \frac{\text{ampere-turns per coil}}{\text{winding ampere-turns}}$
and $\sum_{p=1}^q z = \text{unity.}$

The expression for the axial leakage reactance will be found to be

$$X_y = \frac{4\pi}{10^7} \frac{\omega IN^2}{V} \frac{r}{b} [F(\Delta_p) + F(\Delta_s) + \delta] \quad (13)$$

The value of $F(\Delta)$ depends upon the number of coils and ducts, being $\frac{1}{3}\Delta$ for one coil per winding. These values of $F(\Delta)$ for various numbers of coils are given in Table 1.

Interleaved Windings

A reduction of the axial leakage flux is obtained by interleaving the primary and secondary windings. Although such a procedure is rare with concentric windings, it is not so with sandwich windings, as the magnitude of b is then small.

For the arrangement shown in Fig. 3, where the

secondary is disposed on each side of the primary, the axial leakage reactance is given by

$$X_y = \frac{4\pi}{10^7} \cdot \frac{\omega I N^2}{V} \cdot \frac{r}{b} \left[z_1^2 \left\{ \frac{\Delta_1}{3} + \delta_1 + \Delta_2 \right\} + \Delta_2 \left\{ \frac{1}{3} - z_1 \right\} + (1 - z_1)^2 \left\{ \delta_2 + \frac{\Delta_3}{3} \right\} \right] \quad (14)$$

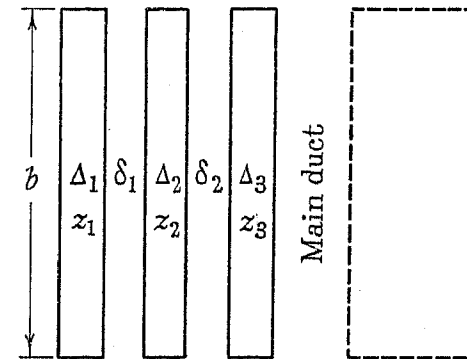
$\frac{1}{2}$ to zero, the axial leakage reactance may be varied in the ratio 1 to 4.

THE LEAKAGE REACTANCE AND FLUX DUE TO π_2

Besides the main axial flux there exists in a transformer another component of flux at right angles to it, this component being termed the radial flux. In a well-

Table 1
AXIAL REACTANCE FACTOR ($F\Delta$)

Number of coils	$z_1 = z_2 = z_3 = \frac{1}{n}$ $\Delta_1 = \Delta_2$, etc., and $\delta_1 = \delta_2$, etc.	$z_1 = z_2 = z_3 = \frac{1}{n}$	
1	$\frac{\Delta_1}{3}$	$\frac{\Delta_1}{3}$	$\frac{\Delta_1}{3}$
2	$\frac{2}{3}\Delta_1 + \frac{\delta_1}{4}$	$\frac{\Delta_1 + 7\Delta_2}{12} + \frac{\delta_1}{4}$	$\frac{\Delta_1}{3}z_1^2 + \Delta_2(z_1 + \frac{1}{3}z_2^2) + \delta_1 z_1^2$
3	$\Delta_1 + \frac{5}{9}\delta_1$	$\frac{\Delta_1 + 7\Delta_2 + 19\Delta_3}{27} + \frac{\delta_1 + 4\delta_2}{9}$	$\frac{\Delta_1}{3}z_1^2 + \Delta_2\{z_1(z_1 + z_2) + \frac{1}{3}z_2^2\} + \Delta_3(z_1 + z_2 + \frac{1}{3}z_3^2) + \delta_1 z_1^2 + \delta_2(z_1 + z_2)^2$
n	$\frac{n\Delta_1}{3} + \frac{(n-1)(2n-1)\delta_1}{6n}$		



where $z_1 = \frac{\text{Ampere-turns of inner secondary coil}}{\text{Total secondary ampere-turns}}$

(Note that $z_1 + z_2 = \text{unity}$.)

Usually the secondary ampere-turns are symmetrically

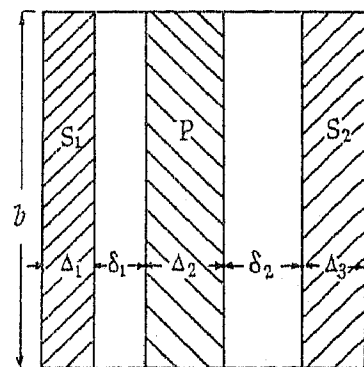


Fig. 3.—Transformer with interleaved windings.

disposed on each side of the primary, i.e. $z_1 = z_2 = \frac{1}{2}$, so that

$$X_y = \frac{4\pi}{10^7} \cdot \frac{\omega I N^2}{V} \cdot \frac{r}{4b} \left[\frac{\Delta_1 + \Delta_2 + \Delta_3}{3} + \delta_1 + \delta_2 \right] \quad (15)$$

Thus by varying z_1 from $\frac{1}{2}$ to unity, and hence z_2 from

designed transformer the radial flux is small, since the additional stresses and losses which it produces are to be avoided. The stresses are axial and may demand massive end-clamping to avoid the windings being displaced under short-circuits. The eddy-current losses⁸ may also be a considerable percentage of the total eddy losses, and cause local heating of the structural ironwork.

Radial leakage flux is produced when there is a dissymmetry between the axial ampere-turn distribution of the primary winding and the secondary winding; radial cooling ducts, tapings, and inter-turn reinforcement of high-voltage windings being the usual causes of axial dissymmetry. As an expression for the total reactance of a transformer must include the radial component, it is necessary to consider the various factors which affect the radial flux.

(A) Radial Ducts in One Winding

If there are q coils in the winding, then the radial flux density of the p th coil is given by

$$B_x = -\frac{4\pi}{10} \frac{IN}{a} \left[y \left\{ \frac{z_p}{h_p} - \frac{1}{b} \right\} + \sum_{p=1}^{q-1} z - \frac{b_p z_p}{h_p} \right] \quad (16)$$

and then, for the p th duct between the p th coil and the $(p + 1)$ th coil,

$$B_x = -\frac{4\pi IN}{10a} \left\{ -\frac{y}{b} + \sum_p^p z \right\} \quad . \quad . \quad (17)$$

where h_p = axial height of p th coil,

g_p = axial height of p th duct,

b_p = distance from boundary to base of p th coil,

b'_p = distance from boundary to base of p th duct,

$z_p = \frac{\text{ampere-turns of } p\text{th coil}}{\text{total ampere-turns}},$

and $\sum_p^q z = \text{unity}$

The radial leakage reactance will then be given by

$$X_x = \frac{4\pi}{10^7} \cdot \frac{\omega IN^2}{V} \cdot \frac{r}{b} \cdot F\left(\frac{g}{a}\right) \quad . \quad . \quad (18)$$

and the values of $F(g/a)$ have been tabulated in Table 2 for various common arrangements of coils and ducts.

(B) Radial Ducts in Both Primary and Secondary Windings

In the previous Section it was assumed that one winding had a perfectly regular distribution of ampere-turns. Conditions are different when ducts are provided in both windings, for the lack of axial symmetry then tends to be restored.

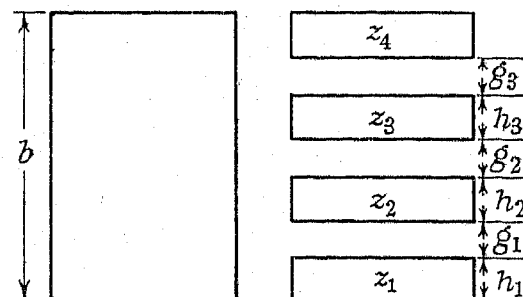
A general treatment of this problem has not been attempted, but it may be of interest to consider the case of one duct in each winding.

For simplicity, suppose each duct has the same axial dimension g . Then there are two extreme conditions (1) the ducts lying along the same x axis (see Fig. 4)

Table 2

RADIAL REACTANCE FACTOR $F\left[\frac{g}{a}\right]$

Number of coils	Number of ducts	$F\left[\frac{g}{a}\right]$ $s_1 = s_2, \text{ etc.}$ $g_1 = g_2, \text{ etc.}$ $h_1 = h_2, \text{ etc.}$	
1	1	$\frac{1}{3} \cdot \frac{g^2}{a}$	$\frac{1}{3} \cdot \frac{g^2}{a}$
	2	$\frac{1}{3} \cdot \frac{g^2}{a}$	$\frac{1}{3a} [g_1^2 + g_2^2 - g_1 g_2]$
2	1	$\frac{1}{12} \cdot \frac{g^2}{a}$	$\frac{1}{3ab} [g_1^3 + h_1 s_1^2 + h_2 s_2^2 - 3g_1 s_1 s_2]$
	2	$\frac{1}{3} \cdot \frac{g^2}{a}$	$\frac{1}{3ab} [g_1^3 + g_2^3 + h_1 s_1^2 + h_2 s_2^2 + 3(s_1 - g_1)(g_1 s_1 + g_2 h_2)]$
	3	$\frac{1}{4} \cdot \frac{g^2}{a}$	$\frac{1}{3ab} [g_1^3 + g_2^3 + g_3^3 + h_1 s_1^2 + h_2 s_2^2 - 3(s_2 - g_3)\{g_2(s_1 - g_1) + h_2 g_3\}]$
3	2	$\frac{1}{9} \cdot \frac{g^2}{a}$	$\frac{1}{3ab} [g_1^3 + g_2^3 + h_1 s_1^2 + h_2 s_2^2 + h_3 s_3^2 + 3g_1 s_1(s_1 - g_1) - 3(s_3 - g_2)\{h_2(s_1 - g_1) - g_2 s_3\}]$
n	$n - 1$	$\frac{n - 1}{6n} \cdot \frac{g^2}{a}$	$X_x = \frac{4\pi}{10^7} \omega \frac{IN^2}{V} \frac{r}{b} F\left(\frac{g}{a}\right)$ where X_x = % radial reactance, IN = total winding ampere-turns, V = voltage of winding, r = length of mean turn, ampere-turns per coil $z = \frac{\quad}{IN}$, $s = bz - h$, $\omega = 2\pi \times \text{frequency}$, a = radial boundary dimension.
	n	$\frac{1}{3} \cdot \frac{g^2}{a}$	
	$n + 1$	$\frac{n + 1}{6n} \cdot \frac{g^2}{a}$	



and (2) the ducts lying at alternate ends of the windings (see Fig. 5).

In the case of (1) the axial ampere-turn distribution

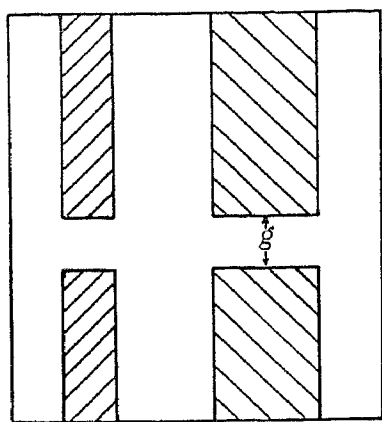


Fig. 4.—Transformer with radial ducts opposite one another and of equal width.

is the same for both windings, so that there is no radial term, i.e. the minimum value.

For case (2) the radial term will have its maximum value.

The radial reactance for condition (2) is given by

$$X_x = \frac{4\pi}{10^7} \cdot \frac{\omega I N^2}{V} \cdot \frac{r}{a} \cdot g^2 \cdot \frac{3h - g}{3h^2} \quad (19)$$

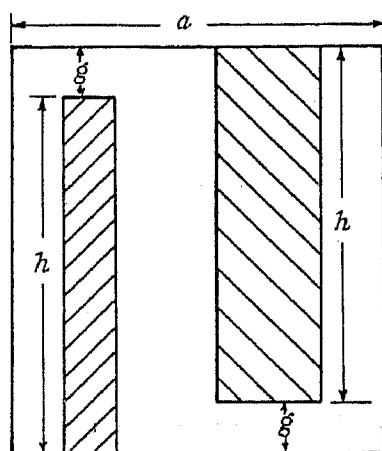


Fig. 5.—Transformer with radial ducts at alternate ends of the windings.

TAPPINGS

The provision of tappings constitutes an important feature of modern transformers. Their inclusion can add greatly to the complexity of the design, the difficulties involved depending solely upon the range of adjustment required. When "on load" tap-changing gear is fitted, it is possible to find a range of adjustment up to 25 %, so that under certain conditions of working one-quarter of a winding may be out of commission.

Unless care be exercised, the "dead" or cut-out portions of a winding can greatly increase the radial leakage flux, and consequently may introduce undesirable effects in the transformer.

It will be realized, upon reflection, that the problem of calculating the magnitude of the radial leakage reactance is simply one of considering any "dead" portions of a winding to constitute a duct. Thus the preceding expressions given under the heading of "radial ducts" can be employed.

Upon further reflection, the steps which need to be taken to reduce the radial field, caused by the cutting-out of portions of the winding, will be apparent. As an example, the usual procedure of taking tappings from the centre of the winding instead of from one end results in a 75 % reduction of the radial reactance.

A further reduction can be secured by splitting the tappings into two groups, one situated at a quarter and the other at three-quarters of the way down the limb.

Another method of reducing the effect of radial flux becomes apparent from consideration of the effects of radial ducts in both windings. The other untapped winding may be spaced by means of radial ducts situated opposite to the tapping positions, so that the ampere-turns per inch distribution of the primary and secondary windings cannot vary widely over the range of adjustment. This method is also employed to reduce the distortion due to end-turn reinforcement.

END-TURN REINFORCEMENT

It is well known that the reinforcement of the end turns of a winding results in an increase in the leakage reactance. This is due to the non-uniform axial distribution of the ampere-turns caused by the additional insulation.

The magnitude of the radial reactance may be computed by means of the expressions given in Table 2.

For the usual case of the reinforcement concentrated in a coil at each end of the winding, the expression for three coils and two ducts may be employed. However, the expression can be simplified owing to the reinforcement being identical at each end.

Therefore

$$X_x = \frac{4\pi}{10^7} \cdot \frac{\omega I N^2}{V} \cdot \frac{1}{3ab} \left\{ 2g_1^3 + 2h_1s_1^2 + \frac{h_2s_2^2}{4} - 3g_1s_1s_2 \right\} \quad (20)$$

where h_1 = axial length of reinforced coil,

h_2 = axial length of normal coils and ducts,

g_1 = axial length of duct between reinforced and normal coils,

$s_1 = bz_1 - h_1$,

$s_2 = bz_2 - h_2$,

$z_1 = \frac{\text{percentage reinforcement at each end}}{100}$,

$z_2 = 1 - 2z_1$.

The disturbance due to end-turn reinforcement may be counteracted by so spacing the other winding that the ampere-turn distributions of the two windings are approximately the same. The above expressions are based on constant axial distribution of ampere-turns in the other winding, and therefore represent the worst condition likely to occur.

THE POTENTIAL VECTOR π_3

The total leakage reactance of a transformer is the combined effect of the three potential vectors π_1 , π_2 and π_3 . The former two have already been considered, and owing to their containing only one variable x or y it was possible to treat each independently. This cannot be done in the case of the third vector, which contains both variables x and y . It is fortunate that

the effect of π_3 upon the total reactance is not so important as that of π_1 and π_2 .

The best way to approach the problem is to consider the conditions necessary to make π_3 vanish. These may be seen to be two, namely:—

- (1) The primary and secondary ampere-turns per cm. of axial length must be equal.
- (2) The position of the axial boundaries must coincide with the extremities of the windings, i.e. $b = h$.

When these conditions are satisfied, $\pi_3 = 0$ and at the same time, because of (1), $\pi_2 = 0$, so that the reactance is that of only π_1 .

PRIMARY AND SECONDARY WINDINGS EQUAL IN HEIGHT BUT LESS THAN BOUNDARY DIMENSION b

Now Condition (1) is satisfied, but not (2); therefore π_3 is no longer zero, even though π_2 is zero.

If the axial boundary be removed to a great distance (see Fig. 6) so that b is very large, then the problem

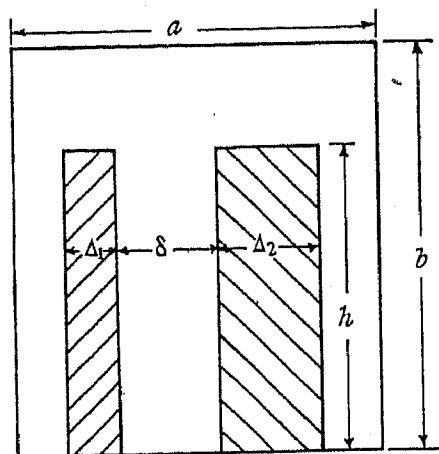


Fig. 6.—Transformer with windings of equal height.

approaches that of “open slot” conditions. This particular problem has been analysed by Rogowski,⁹ who employed a rather different form of potential vector more appropriate to these conditions.

Rogowski obtained a factor which can be employed to modify the value of b , so that a fictitious axial boundary is produced, which only coincides with the extremities of the windings when the axial height is very large compared with the radial width.

The leakage reactance, which may be regarded as axial, owing to π_2 being zero, is given by

$$X_y = \frac{4\pi}{10^7} \cdot \frac{\omega I N^2}{V} \cdot r F\left(\frac{\Delta}{b}\right) \quad (21)$$

$F(\Delta/b)$ containing Rogowski's factor.

Thus $F(\Delta/b)$ is given by the expression

$$\frac{1}{h} \left[1 - \frac{1}{\pi h} \left\{ \left(1 - e^{-\frac{\pi h}{\Delta_1 + \delta + \Delta_2}} \right) (\Delta_1 + \delta + \Delta_2) \right\} \right] \left(\frac{\Delta_1}{3} + \delta + \frac{\Delta_2}{3} \right) \quad (22)$$

where h = axial height of the windings.

When the exponential term is small (this corresponds

to the usual condition for concentric windings), $F(\Delta/b)$ is given by

$$F\left(\frac{\Delta}{b}\right) \simeq \frac{\left(1 - \frac{\Delta_1 + \delta + \Delta_2}{\pi h} \right) \left(\frac{\Delta_1}{3} + \delta + \frac{\Delta_2}{3} \right)}{h} \quad (23)$$

and for high, narrow windings $F(\Delta/b)$ takes the value given in Kapp's original expression¹ in equation (10), i.e.

$$F\left(\frac{\Delta}{b}\right) \simeq \frac{1}{h} \left(\frac{\Delta_1}{3} + \delta + \frac{\Delta_2}{3} \right) \quad (24)$$

ONE WINDING SHORTER THAN THE OTHER, AXIAL BOUNDARIES AT EXTREMITIES OF LONGER WINDING

For this condition neither π_3 nor π_2 is zero, so that both must be taken into account when estimating the total leakage reactance of a system of windings as in Fig. 7.

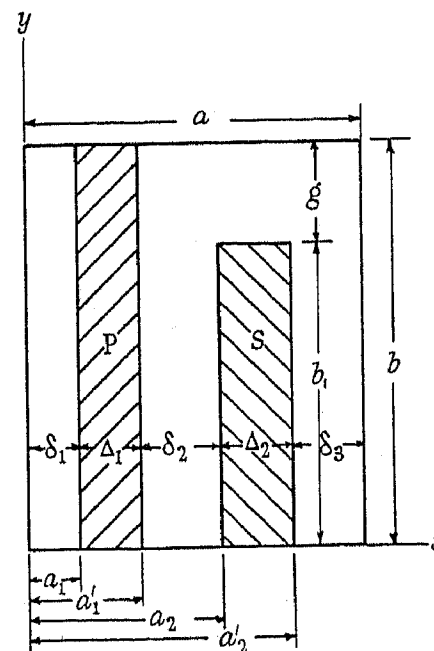


Fig. 7.—Transformer with a radial duct at one end of a secondary winding.

The potential vector takes the general form given in equation (1), with

$$A_{ik} = \frac{16\pi I N}{10abm_in_k(m_i^2 + n_k^2)} \left\{ \frac{\sin m_i a'_1 - \sin m_i a_1}{a'_1 - a_1} \cdot \frac{\sin n_k b}{b} - \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \cdot \frac{\sin n_k b_1}{b_1} \right\} \quad (25)$$

Thus the expressions for π_1 , π_2 and π_3 become

$$\pi_1 = \frac{8\pi I N}{10ab} \sum_{i=2}^{\infty} \frac{\cos m_i x}{m_i^3} \left\{ \frac{\sin m_i a'_1 - \sin m_i a_1}{a'_1 - a_1} - \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \right\} \quad (26)$$

$$\pi_2 = - \frac{8\pi I N}{10ab} \sum_{k=2}^{\infty} \frac{\cos n_k y}{n_k^3} \cdot \frac{\sin n_k b_1}{b_1} \quad (27)$$

$$\pi_3 = -\frac{16\pi IN}{10ab} \sum_{i=2}^{\infty} \sum_{k=2}^{\infty} \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \cdot \frac{\sin n_k b_1}{b_1} \times \frac{\cos m_i x \cdot \cos n_k y}{m_i n_k (m_i^2 + n_k^2)} \quad (28)$$

The first and third of these equations may be combined, so that

$$\pi_{1,3} = \pi_1 + \pi_3 = \frac{8\pi IN}{10ab} \sum_{i=2}^{\infty} \frac{\cos m_i x}{m_i} \left[\frac{\sin m_i a'_1 - \sin m_i a_1}{m_i^2 (a'_1 - a_1)} - \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \left\{ \frac{1}{m_i^2} + 2 \sum_{k=2}^{\infty} \frac{\sin n_k b_1}{b_1} \times \frac{\cos n_k y}{n_k (m_i^2 + n_k^2)} \right\} \right] \quad (29)$$

π_2 gives the radial leakage reactance. This term has already been considered and the appropriate factor for the estimation of the radial leakage reactance may be found in Table 2. For this particular case $F(g/a)$ will be found to be $g^2/(3a)$. If now $\pi_{1,3}$ be considered, it will be found that there are two regions for y , namely $y < b_1$ and $y > b_1$, so that, employing equations (7a) and (7b), (29) becomes

(For $y < b_1$)

$$\pi_{1,3} = \frac{8\pi IN}{10ab} \sum_{i=2}^{\infty} \frac{\cos m_i x}{m_i^3} \left[\frac{\sin m_i a'_1 - \sin m_i a_1}{a'_1 - a_1} - \frac{b}{b_1} \left\{ \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \right\} + \left\{ \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \right\} \frac{b}{b_1} \times \frac{\sinh m_i (b - b_1) \cosh m_i y}{\sinh m_i b} \right] \quad (30)$$

(For $y > b_1$)

$$\pi_{1,3} = \frac{8\pi IN}{10ab} \sum_{i=2}^{\infty} \frac{\cos m_i x}{m_i^3} \left[\frac{\sin m_i a'_1 - \sin m_i a_1}{a'_1 - a_1} - \left\{ \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \right\} \frac{b}{b_1} \times \frac{\sinh m_i b_1 \cosh m_i (b - y)}{\sinh m_i b} \right] \quad (31)$$

The variable y is only contained in the exponential portion of the equation, and if it is possible to neglect its effect upon the value of $\pi_{1,3}$ then conditions are greatly simplified, since there will only be one variable, and one infinite series will have been eliminated.

From consideration of the previous case where the windings were equal in height, it may be seen that the effect of Rogowski's factor⁹ becomes more important the smaller the ratio $b/(\Delta_1 + \delta + \Delta_2)$. It would therefore appear justifiable to neglect the exponential terms except perhaps in extreme conditions when b/a is small. Incidentally, in the present case, the effect of π_2 is important, so that there would appear to be added justification for neglecting the finer correction in the interest of simplicity.

It may therefore be stated, with little error, that $\pi_{1,3}$ gives rise to the axial flux B_y .

THE AXIAL REACTANCE DUE TO $\pi_{1,3}$

Neglecting the exponential term, equation (29) becomes

(For $y < b_1$)

$$\pi_{1,3} \simeq \frac{8\pi IN}{10ab} \sum_{i=2}^{\infty} \frac{\cos m_i x}{m_i^3} \left\{ \frac{\sin m_i a'_1 - \sin m_i a_1}{a'_1 - a_1} - \lambda \cdot \frac{\sin m_i a'_2 - \sin m_i a_2}{a'_2 - a_2} \right\} \quad (32)$$

(For $y > b_1$)

$$\pi_{1,3} \simeq \frac{8\pi IN}{10ab} \sum_{i=2}^{\infty} \frac{\cos m_i x}{m_i^3} \cdot \frac{\sin m_i a'_1 - \sin m_i a_1}{a'_1 - a_1} \quad (33)$$

where

$$\lambda = \frac{b}{b_1}$$

Differentiating these expressions with respect to x and employing equations (6a) and (6b) in order to eliminate the infinite series, enables the axial flux density to be determined over each region of x .

Thus:—

($y < b_1, x < a_1$)

$$B_y = \frac{4\pi IN}{10ab} (\lambda - 1)x$$

($x > a_1 < a'_1$)

$$B_y = \frac{4\pi IN}{10ab} \left\{ \frac{(a + a_1 - a'_1)x - a_1 a}{a'_1 - a_1} + \lambda x \right\}$$

($x > a'_1 < a_2$)

$$B_y = \frac{4\pi IN}{10ab} \{a - x + \lambda x\}$$

($x > a_2 < a'_2$)

$$B_y = \frac{4\pi IN}{10ab} \left[a - x - \lambda \left\{ \frac{(a + a_2 - a'_2)x - a_2 a}{a'_2 - a_2} \right\} \right]$$

($x > a'_2 < a$)

$$B_y = -\frac{4\pi IN}{10ab} (a - x)(\lambda - 1)$$

($y > b_1 < b$)

($x < a_1$)

$$B_y = -\frac{4\pi IN}{10ab} \cdot x$$

($x > a_1 < a'_1$)

$$B_y = \frac{4\pi IN}{10ab} \left\{ \frac{(a + a_1 - a'_1)x - a_1 a}{a'_1 - a_1} \right\}$$

($x > a'_1 < a_2$)

$$B_y = -\frac{4\pi IN}{10ab} (a - x)$$

($x > a_2 < a$)

$$B_y = \frac{4\pi IN}{10ab} (a - x)$$

The total axial leakage reactance is obtained by squaring these values of the flux density and integrating over the appropriate boundaries, when it will be found to be

$$X_y = \frac{4\pi}{10^7} \cdot \frac{\omega I N^2}{V} \cdot \frac{r}{b} \left[\frac{\Delta_1}{3} + \delta_2 + \frac{\lambda \Delta_2}{3} + \frac{\lambda - 1}{3a} \{ a^2 + \Delta_2^2 - 3(\Delta_2 + \delta_3)(a - \delta_3) \} \right] \quad (34)$$

The radial reactance is

$$X_x = \frac{4\pi}{10^7} \cdot \frac{\omega I N^2}{V} \cdot \frac{r}{b} \cdot \frac{g^2}{3a} \quad (35)$$

so that the total leakage reactance is

$$X = x_y + x_x \quad (36)$$

The axial reactance has already been derived for various full-length coil arrangements (see Table 1). No account was, however, taken of any effect of π_3 . A further table (Table 3) has therefore been compiled for various winding arrangements, based upon the results of the Section dealing with the effect of π_3 .

THE BOUNDARIES a AND b

The theoretical analysis, of necessity, assumes that the position of the iron boundaries surrounding the windings is known. When it is required to apply the results of the analysis to an actual transformer, there may appear to be a certain amount of difficulty in determining the boundary positions.

The value of b is fairly easily determined. It is the axial length of the winding, modified when necessary by Rogowski's expression,⁹ or, when equation (34) is employed, it is the length of the longer winding.

On the other hand, the dimension a is not so easily defined, and it is advisable to have recourse to experimental results given by actual transformers. The core circle forms the inner radial boundary, but the outer one is fictitious and is influenced by the tank.

From consideration of the reluctance of two parallel cylinders it is possible to derive an expression for a . Thus

$$a = \frac{r}{\pi} \log \left\{ \frac{c}{d} + \sqrt{\left[\left(\frac{c}{d} \right)^2 - 1} \right] \right\} \quad (37)$$

where c = centre of limbs and d = diameter of core circle.

This may be applied to single-phase units of the two-limb type when there is no metal tank.

In the case of 3-phase transformers, owing to the different reluctances of the centre and outer limbs the radial reactances will differ. The centre limb will therefore have a greater value of a than the outers. The value of a will be found to be given by

$$a = \frac{d_1 r}{\pi k (d + d_1)} \quad (38)$$

where d_1 = distance from core circle to tank wall,
 k = constant having a value of 0.5 to 0.75,
 r = mean perimeter of the windings.

From certain experiments which he has conducted, Heiles⁵ gives the following values to the constant:—

Type of tank	Outer limbs	Centre limb
Rectangular ..	0.7	0.52
Circular-ended ..	0.75	0.52

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APPENDIX 1

Reactance measurements have been made upon two commercial transformers so that these test results could be compared with the calculated values.

A 500-kVA transformer was employed for the first test, with 16½ % of the total turns at the top of the outer winding out of commission. The windings could therefore be represented by Fig. (d) of Table 3.

For the second test the same transformer was employed, but with 9½ % of the turns cut out of the centre of the outer winding; this corresponds to Fig. (f) of Table 3.

A 1 000-kVA unit was employed in the third test, having 9 % of the total turns cut out of the centre of the outer winding.

The radial reactance was determined from Table 2, the radial-reactance factor being $g^2/(3a)$ for Test 1 and $g^2/(12a)$ for Tests 2 and 3.

The value of a was determined from equation (38).

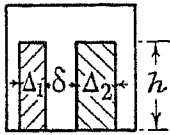
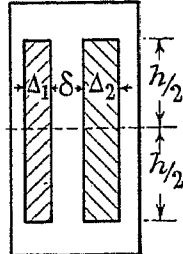
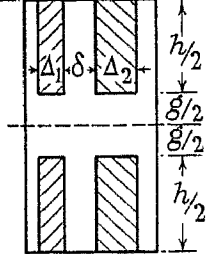
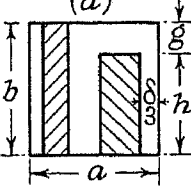
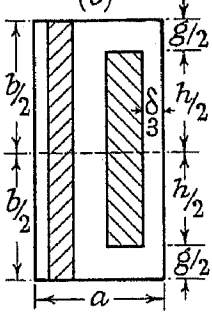
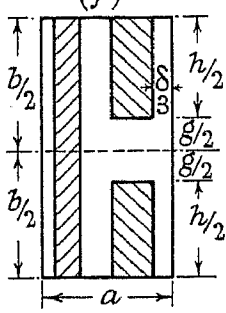
For convenience the results are given in Table 4.

It may be seen that good correlation is obtained between the calculated and test results.

It was thought that it would be of interest to see how the total reactance and its axial and radial components would vary with assumed values of a . The minimum value of a is obviously given when δ_3 is zero, and the upper limit of a was taken as that given by equation (37).

Table 5 shows the results which correspond to Test 1.

Table 3

Arrangement of windings	Axial reactance factor
(a)  (b)  (c)  (d)  (e)  (f) 	$F\left(\frac{\Delta}{b}\right) = \left[1 - \frac{1}{\pi h} \left\{ \left(1 - e^{-\frac{\pi h}{\Delta_1 + \delta + \Delta_2}} \right) (\Delta_1 + \delta + \Delta_2) \right\} \right] \times \frac{\left(\frac{\Delta_1}{3} + \delta + \frac{\Delta_2}{3} \right)}{h}$ $F\left(\frac{\Delta}{b}\right) = \frac{1}{b} \left[\frac{\Delta_1}{3} + \delta_2 + \frac{\lambda \Delta_2}{3} + \frac{\lambda - 1}{3a} \{ a^2 + \Delta_2^2 - 3(\Delta_2 + \delta_3)(a - \delta_3) \} \right]$ where $\lambda = \frac{b}{h}$

$$X_y = \frac{4\pi}{10^7} \omega \frac{IN^2}{V} r F\left(\frac{\Delta}{b}\right)$$

where X_y = % axial reactance, IN = total winding ampere-turns, V = voltage of winding, r = length of mean turn, $\omega = 2\pi \times$ frequency.

Table 4

Test	1		2		3	
	Centre limb	Outer limb	Centre limb	Outer limb	Centre limb	Outer limb
<i>a</i>	10.1	7.52	10.1	7.52	10.7	8
Total reactance (tested)	5.98 %		4.1 %		5.39 %	
Total calculated reactance	5.82 %	6.3 %	3.99 %	3.89 %	5.54 %	5.4 %
Calculated axial reactance	3.49 %	3.16 %	3.8 %	3.63 %	5.27 %	5.03 %
Calculated radial reactance	2.33 %	3.14 %	0.19 %	0.26 %	0.28 %	0.37 %

Table 5

500-KVA TRANSFORMER

δ_3	<i>a</i>	Axial reactance	Radical reactance	Total reactance
0	2.8	2.99	8.42	11.41
2.2	5	2.93	4.72	7.65
4.72	7.52	3.16	3.14	6.30 (outer limb)
6.2	9	3.34	2.62	5.96
7.3	10.1	3.49	2.33	5.82 (centre limb)
9.2	12	3.75	1.96	5.71
12.1	14.9	4.17	1.58	5.75

Tested reactance: 5.68 % out of its tank
5.98 % in its tank

APPENDIX 2

The Derivation of the Axial-Reactance Factors shown in Table 1

The axial-reactance factor for any winding is the sum of the component factors of the coils and of the axial ducts. The expressions for the flux density over the *p*th coil and over the *p*th duct are given by equations (11) and (12) respectively. Squaring these expressions, and integrating the result over the appropriate boundaries, gives the axial-reactance factor of the *p*th coil or the *p*th duct. The limits for *y* are 0 and *b*. The limits for

x of the *p*th coil are $\sum_{p=1}^{p-1} (\Delta + \delta)$ and $\Delta_p + \sum_{p=1}^{p-1} (\Delta + \delta)$.

The limits for x of the p th duct are $\Delta_p + \sum_{p-1}^p (\Delta + \delta)$ and $\sum_p^p (\Delta + \delta)$.

It may therefore be found that the axial-reactance factor for the p th coil is given by

$$f(\Delta_p) = \frac{\Delta_p}{3} \left\{ z_p^2 + 3 \sum_p^p z \sum_{p-1}^{p-1} z \right\} \quad (39)$$

and the axial-reactance factor for the p th duct is given by

$$f(\delta_p) = \delta_p \left(\sum_p^p z \right)^2 \quad (40)$$

Consider the case of a winding having a single axial duct, so that the winding is composed of two coils and $z_1 + z_2 = \text{unity}$.

For the first coil $p = 1$

$$\text{and} \quad f(\Delta_1) = \frac{\Delta_1}{3} \cdot z_1^2$$

For the second coil $p = 2$

$$\text{and} \quad f(\Delta_2) = \frac{\Delta_2}{3} \{ z_2^2 + 3(z_1 + z_2)z_1 \} = \frac{\Delta_2}{3} \{ z_2^2 + 3z_1 \}$$

For the axial duct $p = 1$

$$\text{and} \quad f(\delta_1) = \delta_1 z_1^2$$

Thus the complete axial reactance-factor becomes

$$F(\Delta_p) = \frac{\Delta_1}{3} z_1^2 + \Delta_2 \left\{ z_1 + \frac{z_2^2}{3} \right\} + \delta_1 z_1^2$$

APPENDIX 3

The Derivation of the Radial-Reactance Factors shown in Table 2

The radial-reactance factor for any winding is the sum of the component factors of the coils and of the radial gaps. The flux densities are given by equations (16) and (17), and the components of the radial-reactance factors are given by integrating the square of the flux density over the appropriate boundaries. For the p th coil the limits of integration are 0 and a for x , and b_p and $b_p + h_p$ for y . Similarly, for the p th gap the limits are 0 and a for x , and b'_p and $b'_p + g_p$ for y .

Therefore it may be found that the radial-reactance factor for the p th coil is given by

$$f\left(\frac{h_p}{a}\right) = \frac{h_p}{3ab} \{ s_p^2 + 3Z(s_p + Z) \} \quad (41)$$

where

$$s_p = bz_p - h_p$$

and

$$Z = -b_p + b \sum_{p-1}^{p-1} z.$$

The radial-reactance factor for the p th gap is given by

$$f\left(\frac{g_p}{a}\right) = \frac{g_p}{3ab} \{ g_p^2 + 3Z'(Z' - g_p) \} \quad (42)$$

where

$$Z' = -b'_p + b \sum_p^p z.$$

$$z_p \text{ in this case} = \frac{\text{Ampere-turns in coil below the } p\text{th gap}}{\text{Total winding ampere-turns}}$$

Consider the case of a winding with a radial gap dividing it into two coils. In this case $z_1 + z_2 = \text{unity}$ and $b = h_1 + g_1 + h_2$.

For the first coil $p = 1$, $b_p = 0$ and $Z = 0$.

$$\text{Thus} \quad f\left(\frac{h_1}{a}\right) = \frac{h_1}{3ab} \cdot s_1^2$$

For the second coil $p = 2$, $b_p = b - h_2$ and $Z = -s_2$.

$$\text{Thus} \quad f\left(\frac{h_2}{a}\right) = \frac{h_2}{3ab} \cdot s_2^2$$

For the gap $p = 1$, $b'_p = h_1$, $Z' = s_1$, and $Z' - g_1 = -s_2$.

$$\text{Thus} \quad f\left(\frac{g_1}{a}\right) = \frac{g_1}{3ab} \{ g_1^2 - 3s_1s_2 \}$$

The complete radial-reactance factor for two coils and one radial gap is therefore

$$F\left(\frac{g_1}{a}\right) = \frac{1}{3ab} [h_1s_1^2 + h_2s_2^2 + g_1^3 - 3g_1s_1s_2]$$

when $z_1 = z_2 = \frac{1}{2}$ and $h_1 = h_2$.

Then

$$s_1 = s_2 = \frac{1}{2}b - h = \frac{1}{2}g$$

and

$$F\left(\frac{g}{a}\right) = \frac{g^2}{12a}$$

DISCUSSION ON

"THE CORROSION OF UNDERGROUND CABLES"*

NORTH MIDLAND CENTRE, AT LEEDS, 9TH DECEMBER, 1939

Mr. W. F. Smith: The authors make only meagre references to the possibilities of dealing with the electrolysis trouble by prevention rather than cure. The leakage current that causes this corrosion is due to the difference between the resistances of the return path via the rails and of that via the surrounding earth. This is rather borne out by the fact that if attention is given to the rail section bonding a very decided improvement occurs in the corrosion situation. If the resistance of the return path were reduced by installing a copper feeder alongside the rail, and bonding the two at frequent intervals, a large reduction of leakage current should result. Presumably the authors' reply to such a suggestion will be that the cost would be prohibitive. It is doubtful, however, whether a true comparison of cost has ever been made. Taking into account (1) the cost of repairing the damage which electrolytic corrosion causes to the plant of all authorities concerned, and (2) probable reduction in the cost which is already incurred in the provision of negative feeder cables, I am not so sure that the cost of adopting my suggestion would be prohibitive even if it could not be proved a commercial proposition. This leads up to the question as to the relative magnitude of the chemical corrosion and the corrosion due to electrolysis. If chemical corrosion is the larger component, then we are unlikely to gain very much from the scheme formulated above.

In regard to the test referred to in Table 2, I am not at all clear why it is that with no reversals of current it is possible to obtain a greater amount of corrosion than the figure given as the "equivalent of corrosion." I have read the term "equivalent corrosion" as that arrived at by means of Faraday's laws. The only solution I could find to the problem was that the extra corrosion might possibly be due to the local action which is referred to in the paper as "natural electrolysis." This solution is not, however, thoroughly satisfactory, since, in such a purely experimental case, the plates used would be unlikely to give rise to this local action.

It is also stated with reference to Table 2 that when the amounts of current-flow in the two directions differ only slightly, it is impossible to give a factor relating the actual corrosion with the net current flow. I cannot see why such a factor could not be obtained.

There is one further point on which I should like some information. What is the reason for the use of non-polarizing electrodes, and from what feature do they derive their name?

Mr. A. C. Bailey: I should be glad of further information regarding the cathode effect on lead sheaths. I had thought that this effect was negligible.

* Paper by Dr. W. G. RADLEY and Mr. C. E. RICHARDS (see *Journal I.E.E.*, 1939, 85, p. 685).

I should like to know whether the authors can explain how alternating current causes electrolysis; probably the action is connected with some rectification which may occur at the sheath.

I am associated with an electrical undertaking which has had a number of troubles with plain lead-covered pilot cables in the vicinity of a tramway system. In one case I have in mind the cable was about $\frac{3}{4}$ mile from the tramway system and there were signs of electrolysis at six or seven points along it, about 20 yd. apart. The tests we made on the sheath showed that the current was very spasmodic; from this we concluded that the electrolysis was due to the traction currents. To confirm our conclusion we arranged for the adjacent section of tramway to be shut off during the night, when we made further tests. We found the current to be reduced considerably, but it did not completely disappear. This result showed that return earth currents may cover quite a wide area of ground, as the only section of tramway alive at the time was about $1\frac{1}{2}$ –2 miles away.

Recently I have heard of two water authorities who have experienced trouble with steel water mains. In both cases the main was of 12 in. diameter and the walls about $\frac{3}{16}$ in. thick. In several parts of the main, corrosion had completely eaten through the wall. Measurements showed that there was a direct current flowing. In one case we found nearly 0.5 volt difference of potential between the steel pipe and the surrounding soil. The tests were made with a voltmeter having an internal resistance of 50 000 ohms. It is rather significant that both these steel water mains were connected to cast-iron mains and the joints were of a type permitting electrical continuity, yet the cast-iron pipes did not appear to be affected. The two mains were about 30 miles apart, but exactly the same sort of trouble was experienced in each case—a steady current flowing. In both instances the soil was found to be slightly alkaline. In one case there was a d.c. system a short distance away which I believe was responsible for the trouble; the other case is still under investigation.

Regarding protection against corrosion, the method of direct electrical drainage is convenient where a cable runs alongside the endangered pipe or cable system, but it could not be adopted in the case I have cited of a pilot cable $\frac{3}{4}$ mile away from a traction system. We inserted insulating glands at the joints and, by so doing, practically reduced to zero the current causing the electrolysis.

The authors refer to the relative merits of lead and lead-alloy sheaths from the point of view of resistance to corrosion. Unfortunately, that is not the only aspect to consider. Mechanical considerations such as vibration also have to be borne in mind when choosing the metal

of a sheath. I should like to ask the authors whether the Post Office have laid any plain lead-covered cables in the sea, and, if so, what the experience has been as regards corrosion.

Mr. A. Kelso: From time to time many recommendations are put forward as to how to eliminate corrosion but it appears to me that the most vital thing is the question of cost. We can get over most of our corrosion troubles, but can we do so economically?

Fig. 18 appeals to me particularly; to my mind the easiest way to reduce the potential difference between the lead sheath of a cable and the rail is to increase the conductivity of the rail, but that is seen to be far too costly when one considers that a double-track rail is equivalent in resistance to a copper conductor of about 2 sq. in. cross-section. There is the alternative of bonding the cable to the rail at frequent intervals, but this is subject to the objection that if a fracture of the rails occurs the lead of the cable will be called upon to carry the greater part of the return current.

Of the 41 manholes (Nos. 14 to 54) indicated in Fig. 18 it is only at the first 11 that the potential of the lead of the cable is above the potential of the rail. Would it be an advantage to prepare certain points between manhole No. 14 and manhole No. 24, so that most of the stray current would leave the lead of the cable via special plates, which would be subject to corrosion but could be renewed at frequent intervals and so prolong the life of the cable?

Dr. W. G. Radley and Mr. C. E. Richards (in reply): There is no doubt that, as suggested by Mr. Smith, prevention of electrolysis trouble by the elimination of leakage current from traction systems is preferable to curative measures applied to endangered pipes and cables. Where excessive leakage occurs due to faulty track bonding, etc., attention to the track should be a first step in tackling the problem. The prevention of smaller leakage currents, which may give rise to trouble, is, however, not so easy, and if the solution of this problem is attempted solely by means of negative feeders it may call for a disproportionate expenditure on copper, especially if the feeding distances are long. In such cases the use of negative boosters and the careful balancing of potentials at negative feeding-points is suggested. Taking up the point raised by Mr. Kelso with regard to the protection of the cable system shown in Fig. 18, the cable was actually connected to an earth plate at each of the manholes between 14 and 24, but it is impossible to obtain effective protection in this way by earth plates of practicable size.

As we pointed out in our reply to the discussion before

the Transmission Section, both electrolytic and chemical corrosion are associated with circulating currents, but roughly 50 % of the failures are considered to be due to stray traction currents. It is remarkable how far such currents will travel: an example is quoted in the U.S.A. of a generator causing damage to a pipe-line 400 miles away. We fully appreciate the difficulties experienced by Mr. Bailey in arranging for a shutdown test to determine the source of leakage currents. Apart from currents having their origin in traction systems several miles away which have not been shut down, polarization in the shutdown area is likely to give rise to persistent residual currents.

In reply to Mr. Bailey, corrosion of a lead sheath as a cathode must be attributed to chemical effects due to the concentration of alkali resulting from the passage of the current. It is probable that in most cases a.c. electrolysis is due to incomplete re-deposition during alternate half-cycles. The difference, pointed out by Mr. Smith, in Table 2 between the corrosion equivalent and the corrosion actually measured, may be due to a number of causes. It is thought, however, that it may largely be accounted for by the purely local action (i.e. chemical corrosion) differing slightly from the allowance made for it. The latter was based on a no-current (blank) test. Considering the conditions of the tests—long-time tests with currents which were continually varying—we think the agreement between calculated and experimental figures is reasonable. These variations are also responsible for the fact that it has not yet been possible to put forward a reliable factor relating actual corrosion to net current flow when the net current flow is small compared with the total current flow.

We have no comment to offer regarding the interesting corrosion of steel mains described by Mr. Bailey, except that 0.5-volt difference of potential between a steel pipe and the surrounding soil is adequate to account for serious corrosion. In reply to his inquiry, it is believed that one plain lead-covered cable was laid in the sea in 1937 and is still extant.

Non-polarizing electrodes are single electrodes supplied with an adequate amount of depolarizer. The passage of current through the electrode should be avoided, but if a little current flows the chemical changes at the electrode surface do not affect its potential or build up a back e.m.f. Non-polarizing electrodes are therefore essential as potential standards. The usual lead electrode is satisfactory for very rough work, but in many waters the passage of a minute current may shift the electrode potential possibly a tenth of a volt and so render the measurements useless.

FURTHER CONTRIBUTIONS TO THE DISCUSSION BEFORE THE TRANSMISSION SECTION*

Mr. C. J. Griffiths (Australia) (communicated): Although it is difficult to make a direct comparison of cable-corrosion conditions without taking into account all the circumstances associated with the design and layout of each system, the figure of £48 000 for the replacement of corroded telephone cables during the period 1935–36 suggests that corrosion troubles in Great

Britain are of the same order as those on telephone cables in Australia prior to the general application of remedial measures for damage due to stray-current electrolysis when corrosion costs approximated £9 000 per annum. The cost for corrosion damage on telephone cables in Australia in 1937 was £6 100, representing approximately £34 000 on an equivalent cable mileage to that existing in Great Britain (12 200 000 wire miles referred to on

* See *Journal I.E.E.*, 1939, 85, p. 704.

page 686). It would be interesting to know the proportions of stray-current damage, "natural current" corrosion and chemical corrosion in the total of £48 000. In addition to the electrolysis committees in Sydney, Melbourne and Adelaide, similar committees also now function in Newcastle, Brisbane and Hobart.

Galvanized and black iron pipes have been used extensively for distribution of small cables ranging up to 100-pair capacity. However, considerable corrosion has occurred with this type of construction, particularly in 1- and 2-pair cable sizes, due to what is termed cathodic corrosion. Where the cable system is cathodic due to the pickup of stray current, and the solution surrounding the cable tends to become alkaline, corrosion occurs which is practically identical in appearance to that produced by free-lime corrosion. The latter is referred to on page 692, and it is suggested that it is not strictly correct to say that the corrosion product, pure lead monoxide (PbO), "has never been associated with a definite case of electrolysis."

Wood troughing was used as a conduit for telephone cables in certain instances prior to 1920, but it was generally found that, after a few years, the wood rotted and the duct became clogged with silt.

Unless suitable precautions are taken, it is possible to obtain calibration errors up to 30 % with the circuit arrangement shown in Fig. 8. Apart from the current path along the cable being calibrated, the ammeter A also

tapes wrapped on the cable *in situ*. There is every prospect that this method will provide some reduction in chemical-corrosion damage.

The authors' enthusiasm for the extensive installation of insulating gaps in telephone cable sheaths is not shared in Australia. Apart from the maintenance problem introduced on the telephone cable system, it is felt that it is impracticable to provide reasonably complete protection solely by the use of insulating gaps.

In contrast to the British Post Office, the Australian Post Office is a disciple of electrical drainage as a remedial measure for reducing stray-current damage. At the same time it is realized that some annual charges are involved in maintenance and testing, but, apart from experience in the U.S.A., in this country results over a 10-year period have provided sufficient justification for this method of protection. In addition to the direct protection provided by stray traction currents, an appreciable degree of protection is also provided against "natural current" corrosion. Outside stray-traction-current areas satisfactory protection has been provided in a number of cases of the latter by the installation of zinc earth plates.

In Table 6, which sets out regulations governing stray currents from tramway systems in various countries, the limits applying in Australia refer to regulations in force prior to 1934. In the regulations promulgated in 1934 the limits set out in Table A herewith apply.

Table A

Country	Allowed voltage drop on track, volts per half-mile (1)	Allowed p.d. (in volts) between track and pipes (2)	Period of observation for voltage	Resistance (ohms) of rail bonds:—	
				In yards of rail	Percentage overall increase in resistance of track
Australia	Separate roadbed 2.0 In roadway .. 1.0	0.8 (cable positive)	24-hour algebraic average (week-day)	3	10

measures an appreciable by-pass current from the cable sheath through the earth beyond the calibrated section.

Some use was made of a Haber earth-current meter in 1929 for electrolysis testing, but it was subsequently discarded as too cumbersome, and in its place the Bristol smoke chart recording voltmeter and the mirror type recording galvanometer were employed.

With the adoption of electrical drainage, protective coverings have not been used as a stray-current electrolysis preventive measure, and only isolated use of coverings has been made for chemical-corrosion conditions. The latter cases are determined by resistivity surveys, chemical analysis of soil conditions or previous fault experience. Owing to the comparatively small annual cost of repairs, the chemical-corrosion damage provides little economical justification for any appreciable additional expenditure on protective coverings. In the country districts of Australia it is the practice to lay unarmoured lead-covered cables direct in the ground, and for chemical corrosion on cables of this type experiments are at present being carried out with rubber wax

Mr. C. M. Longfield (Australia) (*communicated*): In stating that their experiments on alternating currents of low frequency and on reversing currents cause appreciable corrosion, the authors confirm experience obtained elsewhere and in particular in Melbourne, where bare lead-covered cables have failed in those cases where reversals of polarity occur. For this reason, every endeavour is made to maintain all such cables cathodic to their surrounding electrolyte.

On page 692, the authors state that electrolysis is characterized by steep-sided pits and by preferential attack along crystal boundaries. Do they intend this to include natural-current electrolysis as defined on page 688? If so, have they any idea of the differences of potential that are likely to be created by inhomogeneities in the metal-liquid interfaces? If these potentials are sufficient to cause the same kind of pitting and the production of end products rich in chloride, as would be the case in stray-current attack, then chemical and microscopic investigations fail as criteria in distinguishing stray-current electrolysis from electrolysis due

to other causes. Mr. Beckinsale's remarks suggest that this is so, and my own experience* indicates that considerable caution must be exercised in drawing conclusions from chemical tests. It is suggested that, in important and doubtful cases, a lead specimen might be connected metallically to the lead sheathing of the cable and suspended in the water in the manhole. The progress of corrosion on this specimen might then be compared with that on a similar specimen also suspended in the duct water but insulated from the cable sheath.

The authors describe several methods of conducting field tests to detect the discharge of current from cable sheaths, and quite rightly conclude that there are no satisfactory means of measuring the current density of discharge from point to point along a cable run. After many years of experience of field testing in Melbourne, and after trying and rejecting most, if not all, of the methods described, our experience here has taught us that the only satisfactory test, even though it be a qualitative one, is the 24-hour record of p.d. between cable and earth electrode. This is frequently combined with simultaneous correlation tests. The current-difference test described by the authors on pages 695 and 696 is very difficult to apply; it does not reveal the conditions depicted in Fig. 15, and cannot be used where several cables are bonded together in a duct-way. It can generally only be carried out over short periods of time, during which the electric-tramway conditions may not be representative.

The network described in relation to Fig. 9 is probably erroneously attributed to C. and M. Schlumberger. I believe J. M. Pearson, of Philadelphia, was responsible for this modification of Schlumberger's three-electrode method, which can only be successfully used if the potential differences to be measured are large compared with the differences in the electrode potentials of the three electrodes, if the ground surface is not too hard or too dry and if the potentials it is desired to measure are not masked by the presence of other adjacent pipes or cables. It seems clear that C. and M. Schlumberger† encountered some of these difficulties, since, in their field tests, they expressed the indications as a ratio using a second but stationary network as a reference. The results of this method produced the diagram given by the authors in Fig. 10, but from this it is only possible to conclude that the buried pipe or cable is *exchanging* current with the earth, a piece of information which can be obtained much more readily and conclusively by the four-electrode method described in my 1935 paper.‡

The exploring half-cell referred to in Fig. 13 is an interesting development which may, with experience, yield satisfactory results. It is understood that the survey represented by Fig. 15 relates to "steady" potentials and not those due to stray traction current. Would the authors make this point clear? As oxygen concentration plays a large part in the corrosion cell, would the authors give their opinion upon the possible influence the occurrence of water-filled depressions in the spare duct is likely to have upon the observed results?

The addition of sodium silicate to the cable-pulling

compound is a very interesting development. It would appear that the net result is to produce a threshold potential below which corrosion will be inappreciable. If this is so, can the authors give an indication of its magnitude?

It is noted with interest that the British Post Office has relied mainly upon insulating joints for protection against electrolysis. Although statutory rules have been in force in Melbourne for a long period of years and were revised a short time ago, electrical drainage has been found necessary and generally satisfactory, while insulating joints have been used very sparingly as their introduction proved a failure in most cases tried. The presence of large steel pipes which could not be similarly treated may have influenced the situation somewhat. Surely the Milan case quoted by the authors is an exaggerated one.

It seems to be now generally accepted that a reduction of potential on uninsulated rails will not completely remove the stray-current electrolysis hazard. It is quite clear from field investigations in Melbourne that a linear relation between rail voltage-drop and current in a buried pipe or cable can be expected and that corrosion will occur under the stimulus of such stray currents, however small, provided the buried metal does not develop a threshold potential (see previous reference to *Electrical Engineering*).

Prof. Watson's remarks at the London discussion on the paper are of special interest, and his statement that corrosion frequently follows pulling-in strains can be amply confirmed by experience in Melbourne. We have also applied zinc earth-plates quite successfully to small lead-covered cables. S. C. Bartholomew* referred to an early German example of this nature.

Referring to Mr. Frost's remarks, it is of interest to note that power cables drawn into ducts in one city in Australia are protected by electrolysis-proof paper tapes over which is a jute layer underneath bare galvanized-steel wire armouring. Cables protected in this manner are electrolysis-proof and can be withdrawn from the ducts without difficulty. If the armouring is discontinuous at manholes, the effect of numerous insulating joints is secured yet the arrangement is not subject to the objections raised by Mr. Frost.

I disagree with Mr. Gould's statement that the standard of trackwork in Australia is inferior to that in England. Is it not rather a question of local conditions, e.g. soil conductivity?

In conclusion, I should like to ask the authors why the British Post Office connects cables to earth plates at manholes. Surely the resistance of the cable with respect to earth is so low already that an isolated earth plate could scarcely compete with it.

Dr. W. G. Radley and Mr. C. E. Richards (in reply): In reply to Mr. Griffiths, it is impossible to give any more detailed division between damage due to stray current, natural current and chemical corrosion than will be found in our answer to previous discussions. It is assumed that, at least before remedial measures were instituted, damage due to stray-current electrolysis formed a larger proportion of the total in Australia than

* See "Stray-current Electrolysis—Some Fundamentals," *Electrical Engineering*, 1938, 57, p. 67.

† *Annales des Postes, Télégraphes et Téléphones*, 1932, 21, p. 745.

‡ *Journal I.E.E.*, 1935, 76, p. 101.

* Institution of Post Office Electrical Engineers, Professional Paper No. 89, 1922.

in this country. This would result from the fact that in Australia a relatively greater proportion of the total cable network is concentrated in a few large cities and was therefore exposed to the stray-current hazard. In this country it has been found economically worth while to pay attention to cables subject to chemical corrosion.

Instances of cathodic corrosion, such as those described as occurring with small distribution cables in iron pipes, have not been encountered in this country. The phenomena are, however, such as would, from theoretical grounds, be associated with cathodic corrosion, but the conditions are rare in practice and have not been observed.

If Mr. Griffiths's remarks concerning Fig. 8 have been rightly interpreted, Australian practice would appear to involve calibration of the galvanometer by passing a high measured current from the battery through the cable and its subsequent use for direct measurement of the stray current. Errors may arise during the calibration due to by-pass of the current, but with the usual British systems of cable layout and bonding these would never exceed 5 %. The method described in the paper is a "null" method and does not involve calibration.

Post Office experience with insulating gaps is based on the installation of some thousands in selected positions. It is appreciated that, where the conditions are such as to make it worth while, more complete protection could, in some cases, be provided by drainage. There have been no maintenance problems with the insulating gaps.

We thank Mr. Griffiths for bringing Table 6 up to date.

With reference to Mr. Longfield's communication, electrolysis, by definition, comprises that due to the flow of self-generated as well as stray currents. The differences of potential giving rise to the flow of current in the former case may be of the order of 0.1 volt. Both kinds of electrolysis produce the same type of attack, and it is usually impossible to distinguish between them solely by means of chemical and microscopic investigations. The suggested test, in which two lead specimens are suspended in the manhole water, would not help because one of these would, and the other would not, form a path for the flow of the stray current whatever its source. Some electrical study of the current circulating in the cable sheath-earth path is essential to the determination of its origin.

The current-difference test described on pages 695-696

demands a practised technique for successful application. Admittedly it does not reveal the varying conditions along the duct line between points of measurement such as are exhibited by Fig. 15. This, incidentally, relates to steady potentials. By simple rearrangement of the bonds the current-difference test can be utilized where cables are bonded together, and continuous tests have been made for periods of over 8 hours. Records of the p.d. between cables and an earth electrode are of no more than qualitative value, owing to the fact that the resistance of the cable sheath-earth path is a deciding factor in the current flow. They may be definitely misleading if the possible errors described on page 696 are not borne in mind. With the Gibrat modification of the Schlumberger method it is theoretically possible to calibrate the three-electrode equipment so that the current-interchange between a buried pipe and the earth is quantitatively measured. We have no first-hand experience with the method, but we believe that it is difficult to manipulate in practice.

In our opinion the state of aeration of the water in a duct through which an exploring half-cell is pulled will have no effect except in measurements of the "rest potential." It is not thought that the addition of sodium silicate to the cable-pulling compound would appreciably increase the "threshold potential," but it would reduce the current flowing when the potential difference was low.

The British Post Office realizes the limitations of insulating joints as a method of protection against electrolysis. Their location must be carefully planned, but in very many cases, where the layout of the underground system is comparatively simple, experience over a number of years shows that their use can be most effective. The Milan system was described as operating in 1937. The track maintenance was bad.

With reference to the comment on Mr. Frost's remarks, the cable described by Mr. Longfield is essentially an armoured one and does not come into the same category as those referred to by Mr. Frost. It has for a long period been standard practice to connect cables to earth plates at manholes where the cable is normally at a positive potential with respect to earth. The additional cost is small, but it is realized that the added protection is also small, especially when the duct line is wet.

Mr. Longfield's other remarks do not call for reply, but form a valuable addition to the available information on the subject.

DISCUSSION ON

"A MEANS OF PROVIDING CONTROLLED ACCELERATION AND DECELERATION AND ALSO CONTROLLED REGENERATIVE EMERGENCY BRAKING ON WARD-LEONARD MINE HOISTS"*

Mr. J. Bentley (*communicated*): A system of control which will provide uniform acceleration and retardation would go far to eliminate the kinetic stresses in mining hoist ropes. These ropes have necessarily to be of such a size that there is a very limited factor of safety; and for this reason the stresses operating should be accurately determined. The author has apparently come to the decision that the stresses on the ropes of the mine hoist under his observation are not sufficiently controlled, and a more uniform retardation is required.

For control systems, regenerative braking has an advantage over mechanical braking in that the current regenerated is a measure of the torque being transmitted, provided the field strength of the motor acting as a generator is constant.

The inertia of the equipment is mainly associated with the rotary parts, and therefore can be taken as constant. The load on the rope, which is variable, acts to assist or retard the braking effort. Figs. 2 and 3 confirm this.

The author's system depends for its success upon the control exciter varying the excitation supplied to the generator in accordance with the latter's field characteristic. The excitation when generating should be higher than when motoring by a fixed amount, sufficient to supply a voltage that will pass a predetermined current through the ohmic resistance of a circuit made up of the motor, the generator armatures and the line cables. This circuit is necessarily of low ohmic value, and any alteration of the contact resistances would have a large effect on the current flowing. Also, while the terminal voltage at the exciter can be made to follow the field characteristic of the generator very closely, the variation of the ohmic value of the various field windings due to change of temperature will prevent the voltage values remaining constant. I suggest that it would be desirable to fit to the exciter a governing winding carrying the generated current.

The author does not give an indication as to the variation, if any, of the generated current. A curve showing this would have been more convincing than the figures given for the time of the retardation. These might equally well be the result of non-uniform retardation.

Regarding the correction to the value of the braking effort on account of the bi-conical drum, it would be interesting to know why advantage cannot be taken of the extra retardation available, providing this retardation is uniform.

It is not clear from the paper how the correction for variable loading is applied. Is the point at which the slowing-down device comes into action varied to suit the loading automatically?

In my opinion automatic control of the acceleration and retardation should be the normal method of operation. Also, if the alternative emergency braking is mechanical, it is necessary for this to be efficient and give uniform retardation. Under the emergency condition when the rate of retardation has to be increased, it is all the more necessary for the rate to be uniform.

Any circuit which for safety reasons has to be complete should be permanently connected, and any inclusion of contactor or other movable contacts should be avoided. For instance, the principle advocated by the author could be applied as shown in Fig. A. With this layout the circuit is permanently complete. The hoist will be accelerated when the separate excitation is applied to the generator and retarded when it is cut off. It also takes out of the operator's hands the fixing of the rate of acceleration and retardation. The system would necessitate the speed being read from the speed indicator and not from the position of the operating lever.

Overspeeding of the motor-generator, and failure of the regenerative braking at the hoist due to the main supply failing, are best provided against by the fitting of a centrifugal brake on the motor-generator shaft. The centrifugal brake comes into action at a speed above the normal speed of the motor-generator when regenerating. This fitment is in common use on the motor-generators controlling heavy derrick winches on board ship.

I have found that these brakes are very reliable and give very uniform retardation. They are not subject to the difficulty arising out of the lack of consistency of the braking coefficient of the surface material which so commonly affects mechanical braking, because any momentary extra braking is levelled out by a momentary reduction in the speed.

The author records the fact that the mechanical brake has a time-delay; this factor, which is consistently ignored by designers of brakes, has a bearing on the success or failure of many braking schemes.

Mr. J. Kirkwood (*communicated*): The scheme devised by the author is a distinct advance in the art of electric winding and he is to be congratulated on the success obtained on the application of the scheme to actual winding conditions. Its greatest application will be on deep shaft winders, owing to the lower factor of safety of the ropes and the necessity to prevent undue stresses on regenerative emergency braking. At the same time the system would be equally desirable on shallower shafts, in that controlled acceleration and retardation at any part of the wind is a distinct asset.

The author implies that his scheme uses the standard acceleration and retardation cams, but it seems obvious that the acceleration cams are redundant and could be

* Paper by Mr. H. FREEMAN (see *Journal I.E.E.*, 1939, 85, p. 713).

omitted without affecting the safe and efficient operation of the plant.

He mentions that regenerative braking is not permissible on overspeed of the convertor set, and consequently he has arranged his control gear so that in such an emergency excitation is removed from all machines and the brake solenoid; so that, with the latter de-energized, the emergency mechanical brakes are applied. Now overspeed of the convertor set is usually caused by failure of supply, and it seems to me that protection should be initiated immediately the supply fails and not delayed until the convertor set has reached a pre-determined speed. Further, there is an element of danger in confining the protection to the emergency mechanical brakes, as it is well known that there is an inherent time-lag in their application after the brake solenoid has been de-energized. This element of danger applies not only to overspeed of the convertor set but to

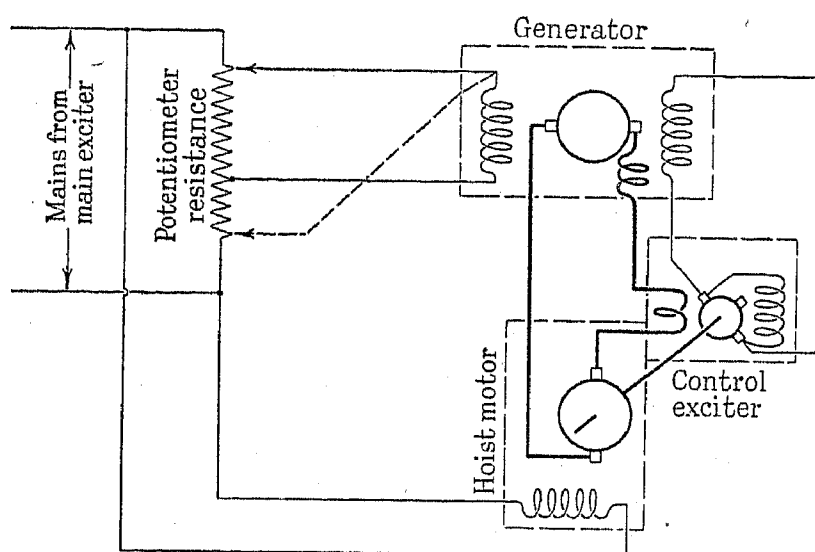


Fig. A

NOTE.—The series winding on the generator opposes the shunt field, and its purpose is to kill the residual magnetism.

the winder speed itself when loads are being lowered. I would suggest that in cases of supply failure, particularly when there is no flywheel coupled to the set, the control gear should be arranged to open the main circuit between generator and winding motor, thus protecting the set against overspeed, and that at the same time a resistor should be inserted across the winding-motor armature terminals to give dynamic braking of the winding motor sufficient to prevent overspeeding of a descending load or even to reduce its speed until the mechanical brakes come on. It would, of course, be necessary to maintain the winding-motor field in such an emergency.

Mr. T. H. Petch (*communicated*): The author gives on page 718 the variations in deceleration time obtained with his system when applied to the Gifford's winder. The calculated times (on which Figs. 2 and 3 are evidently based) vary between 8 and 20 sec. It is to be noted that the wide variation in times, as between 8 and 20 sec., is partly accounted for by the different winder speeds at the beginning of the deceleration periods. Since there is a fixed gear ratio between the control exciter and the winder itself, the speed of the control exciter is a measure of the winder speed. Figs. 2 and 3 show exciter speeds of 280 and 403 r.p.m. respectively at the commencement of the deceleration period.

Speed regulation is a matter of some importance on electric winders, and from the point of view of ease of control and maintenance of output it is usually considered very desirable to keep the speed regulation as small as possible. It is somewhat surprising, therefore, to see mention of such a big regulation as is implied by the difference between the speeds 403 r.p.m. and 280 r.p.m. even when these apply to lowering and raising a full load near the bottom of the shaft.

It is frequently necessary with a Ward-Leonard winder, in order to provide for stability, to have on the generator a differential compound winding, and the necessary application of such a winding sometimes tends to make the speed regulation of a winder worse than is desirable. Even supposing that this happens to be the case in the present instance, it is hardly to be expected that even then the speed variation would be so large as on the Gifford's winder. It appears possible, therefore, that the arrangement of exciters adopted by the author tends to impair the speed regulation of the winder as a whole, this being very probably due to the generator excitation itself being partly dependent on the actual winder speed, as will be seen from Fig. 1.

As regards the acceleration and deceleration cams which are normally fitted to Ward-Leonard winders, it would seem from the paper that the acceleration cams could be eliminated, but it is not clear that this is proposed. On the other hand, the deceleration cams ought not to be dispensed with as they can still perform their very useful function of bringing the winder to low speed before the end of a wind, and thus provide a considerable amount of protection against the up-coming cage or skip running too far into the headgear.

The decelerating cams are dependent on distance for their operation, and therefore must be arranged so that the driver's operating lever is brought back to the neutral position early enough and quickly enough.

With the author's system there would appear to be difficulty in arranging for satisfactory operation of the decelerating cams. Suppose that the speed of the winder corresponding to the control-exciter speed of 403 r.p.m. is v ft. per sec. In order to provide adequate protection for lowering a load, where a stop is to be made from a speed v ft. per sec. in 20 sec. (the time shown in Fig. 3 as corresponding to 403 r.p.m.), the driver's control lever must presumably be moved fairly rapidly to the neutral position at a distance from the end of the wind which is dependent on the speed v and the time of retardation (20 sec.). If it is assumed that the rate of deceleration is constant, this distance will be $v \times 20/2$ ft.

If now this setting of cams is used to bring the driver's control lever to the neutral position during normal winding, i.e. when raising a loaded cage, the lever is brought to the neutral position much too early. Supposing the speed at the end of the wind, when raising a load, is v' ft. per sec. (v' being less than v) and taking the author's figure for deceleration time of 10 sec. and again assuming a constant rate of deceleration, the distance travelled will be only $v' \times 10/2$ ft. per sec. The result will be that the winder will stop much too early, since $v' \times 10/2$ is very much less than $v \times 20/2$.

A creeping speed is generally allowed after the cams have taken effect. The distance (feet) to be travelled at

creeping speed would then approach $\frac{1}{2}(v \times 20) - \frac{1}{2}(v' \times 10)$ and would add so much to the time of the normal wind as seriously to impair the output.

Even if the rate of retardation were not constant, there would still be a difference in the stopping distances between descending and ascending loads.

The same difficulty applies to the setting of any device used for protecting against overspeed and overwind. If set to give adequate protection for the lowering of a load, then the device would impose such severe restriction on speed when raising a load that comparatively long periods of time at creeping speeds would be necessary, again seriously impairing the output.

The author states that the following three methods of controlling the generator field current are available: arranging that the field current is at a certain value (a) when the winder has travelled a given distance during retardation; (b) after the expiration of a given time during retardation; (c) at a given speed of the winder during deceleration. The apparent difficulties described above are all due to adopting Method (c).

From the point of view of arranging for satisfactory operation of the deceleration cams, or of the overwind and overspeed device during the deceleration period, obviously, since these devices are dependent on distance, Method (a) is the best. With this method the speed of the winder must correspond, as closely as speed regulation will permit, to the position of the Ward-Leonard controller, and the time-constant of this generator field will have little effect. The ideal to be aimed at is to have the winder always stopped at the correct position at the end of its wind, irrespective of the loading conditions. Speed regulation makes this difficult, and yet speed regulation is necessary in order that the winder may be stable in operation.

As regards Method (b), if the start of deceleration at the end of the trip is always made when the cage is at the same distance from the bank, and if the rate of deceleration is controlled consistently on a time basis, the result is practically the same as is given by Method (a). Any difference is due to variations in the load, which is only a part of the total forces involved, since the inertia of the moving parts is comparable with the net load and has to be included in the forces opposed during deceleration.

Method (c), however, does not depend directly on either distance or time but only on the winder speed, which, in turn, is dependent on the load and on the speed regulation of the machines. There is no independent reference to distance or time, and it is not clear how the point at which the deceleration is to be commenced can be determined. It would therefore seem that, from the point of view of the safe operation of the winder, Method (b) is preferable to Method (c).

Method (b) has been satisfactorily used in some modern large winders with which I have had experience. It was developed originally for automatic, smooth and rapid emergency braking, and later to give, in addition, controlled acceleration and deceleration during normal working, independent of the driver. The scheme is very simple and reliable, and consists essentially of a small motor with a flywheel mounted on its shaft extension, connected across the field of the generator exciter.

During the acceleration the rate of increase of voltage across the generator exciter field is dependent on the rate of acceleration of the motor driving the flywheel, while during deceleration the generator exciter field is maintained by the energy supplied by the flywheel, with the small motor now acting as a generator. This device operates solely on a time basis and, of course, different times can be obtained by varying the size of the flywheel or by placing a variable loading resistor in parallel with the generator exciter field. The motor is usually of about 1 h.p. rating and the flywheel is generally composed of a number of steel discs, $8\frac{1}{2}$ in. diameter, varying in width from $\frac{1}{4}$ in. to 1 in. This gives a means of adjusting permanently flywheel size to suit the requirements of the individual case.

In a recent example the aims have been to give deceleration times which will be practically constant, irrespective of the loading conditions, and to have the deceleration time the same as the acceleration time. Provision is made whereby it is possible, if so desired, to have the emergency braking time rather shorter than the normal deceleration time, thus giving a greater rate of deceleration. It will be seen that, as the timing device is here an entirely independent device and is in no way dependent on the winder speed, there is no question of impairing the speed regulation of the winder.

As regards the flywheel and motor device described above, it is a simple matter to cut this out of action when the deceleration cam begins to take effect and to revert to the conditions that apply with Method (a) if this is preferred; only it should be pointed out that if this is done the protection against the driver moving his lever too quickly to the neutral position, during the period where the decelerating cam is operating, is lost.

It would be interesting to know how manœuvring control is affected by the author's scheme. Owing to the fact that the effect on the main generator voltage is not immediate and that there is always a time-delay before the required voltage is reached, it would seem that this sluggishness would make control at low speeds somewhat difficult. Where the flywheel and motor arrangement is used for timing the rate of increase of the generator exciter voltage and therefore of the generator voltage, the method of overcoming this difficulty is to have two field windings on the main generator. The first of these, the auxiliary field, is under the direct control of the master controller, so that for low speeds the normal rigid control usually associated with Ward-Leonard winders is employed, giving immediate response to the movement of the driver's control lever. The second of the two fields, the main field, comes under the influence of the device controlling acceleration and deceleration only at a speed above manœuvring speeds.

For the particular winder described by the author, there is evidently latitude as between the maximum permissible rate of deceleration and the normal rate of deceleration. The maximum deceleration is that which should not cause serious discomfort to men riding in the cages. If, however, the normal rates of deceleration are already close to the limits, there seems to be no particular reason for applying a scheme which gives variable emergency regenerative braking times, since an emergency braking time should not exceed a normal braking

time. That which applies for a particular case, therefore, will not always apply to every case.

In the author's scheme it would appear that the difference in regenerative emergency braking times is partly due to changes of resistance and partly to an automatic effect due to the arrangement of exciters.

Mr. H. Freeman (*in reply*): In reply to Mr. Bentley, it was the desirability of being able to predict and control at least the stresses applied to winding ropes, particularly on very deep winders, which first led me to search for a suitable method of attaining these ends. The reason why the gear was fitted to the Gifford's Shaft winder of the Champion Reef Company was the fact that the Company was particularly interested in winding questions as plans were being made to deepen and equip Gifford's Shaft to a vertical depth of 6 550 ft., and kindly offered all facilities for tests and experiments in view of the importance of the problems involved.

Mr. Bentley states that figures given for the time of retardation may equally well be the result of non-uniform retardation. Such is not the case. Figs. 2 and 3 give the rates at which the generator field current must decay to produce a constant retarding current for the stated time, position of cages, and conditions of cage loads. These curves were calculated from the magnetization curve of the generator, the resistances of the generator and motor armatures and busbars, observations and measurements of the effects of armature reaction, and also allowing for increase of the convertor-set speed during retardation. These were later verified by recording the generator field decay during test retardations. The control exciter was then designed to provide these characteristic curves as nearly as possible, and the resulting product gave curves which deviated remarkably little from those required. The winder-motor load current just before a trip occurs, in the conditions represented in Fig. 2, is 1 900 amp. (motoring). On the occurrence of the trip this falls to 150 amp. (regenerating), and this value remains constant until the mechanical brakes are applied. Similarly, in conditions represented in Fig. 3, the armature current is 1 700 amp. (regenerative) before the trip and rises to 3 200 amp. (regenerative) during retardation. Incidentally, the peak capacity of the winder motor is about 3 150 amp. The method of determining the two extremes of time limits is described in my reply to Mr. Petch.

I do not think that a governing winding fitted to the exciter as Mr. Bentley suggests would be desirable, as it would distort the output of the control exciter from the characteristic required.

There is no reason why, in the case of the bi-conical drum, use should not be made of both the drum and the motor, providing the retardation is uniform (as Mr. Bentley suggests) and its value is consistent with safety to men and machinery.

The correction of deceleration time is purely automatic and is brought about by the cage loads themselves. For instance, referring to the figures given on page 718, the first and third sets of values are those for trips with the cages at the same position in the shaft in both cases. In the first case the load was in the upcoming cage and was therefore itself helping to retard the hoist, the resulting deceleration time being 8.6 sec. In the other case,

however, the load was in the downgoing cage and had to be itself retarded, with the result that the deceleration time was lengthened to 15 sec.

As pointed out in my reply to Mr. Petch, the system is primarily designed to prevent abnormal use of the winder. There is no doubt that it could be used for purely normal operation, but this would involve the provision of means for commencing retardation at different points near the end of the wind to compensate for varying loads, and I think that the present system of retarding cams is simple enough and satisfactory for most purposes.

The modification of the system suggested by Mr. Bentley has in my opinion two drawbacks:—

(1) The control exciter as shown in Fig A shares in the excitation of the generator, and as the output of the control exciter would increase with the speed of the winder the generator excitation would be continually increasing, with a consequent further increase of winder speed. Unless the generator field was designed to work at a high magnetic saturation for a normal speed of the winder the latter would tend to run away when heavy loads were being lowered.

(2) The modification would necessitate specially designed generators with two field windings, whereas the system as it stands can be fitted to any existing winder, the only alteration necessary being to the resistance values in the Ward-Leonard controller.

As regards prevention of overspeed of the convertor set, there are many diverse opinions as to how this is best accomplished. A centrifugal brake would no doubt be satisfactory on comparatively small sets, but I doubt whether it would be suitable for sets of dimensions common to most mine winders.

In reply to Mr. Petch, I may say that the winder-speed variations mentioned in the paper were taken from the winder before my device was fitted, and have in no way been altered by it. For the control exciter to affect this it would be necessary for it to share in the excitation of the main generator. This it does not do in normal winding—in fact, it is then actually motoring. I will refer to this matter again later.

The speed of the winder is 35 r.p.m. at full rated voltage. The convertor set is operating with a slip of 15 %, and as the generator is provided only with straight-forward compensating windings and its excitation is constant it follows that the voltage and thus the winder speed will be down by 15 % when the cage load is such as to demand this slip. This occurs shortly after the end of the acceleration period with a fully loaded up-cage, and in these conditions the winder speed would be 29.75 r.p.m. The difference between this and the 28 r.p.m. mentioned in the paper is accounted for by armature reaction. Incidentally, the winder motor is not fitted with compensating windings. With a fully loaded up-cage the full-speed portion of the wind varies from 28 to 36 r.p.m. On the other hand, with a fully loaded down-cage and empty up-cage, more power is returned to the convertor set by the winder than is taken from it, with the result that in the latter part of the wind the convertor set overspeeds to an extent of 8 %. This is again reflected in the winder speed, which would therefore be 37.8 r.p.m. Again, the difference between this

and 40.3 is accounted for by armature reaction, the winder motor in this case of course is acting as a generator. The full-speed portion of the wind with a fully loaded down-cage varies from 31.5 to 40.3 r.p.m. This amount of regulation is not so marked with straight Ward-Leonard sets, but is unavoidable to a more or less marked degree on Ilgner sets, unless some sort of provision is made on the generator field system to compensate for it.

The object of the scheme is not to interfere in any way with the normal operation of the winder; consequently the accelerating and decelerating cams are still in use—in fact the latter could hardly be dispensed with. On Gifford's winder the approximate time of retardation provided by the cams is 24 sec. According to the figures on page 718 of the paper the longest decelerating time provided by the control system under the worst conditions is 20 sec. Now although any longer time than this may be taken, the nature of the system prevents deceleration in a shorter time. The cams therefore have 4 sec. to spare under the worst conditions. In other words, the system fixes the maximum rate of retardation and therefore the maximum stress on the rope: similarly with acceleration. These functions it will perform at any point in the wind, the rates being fixed by the position in the shaft and the cage loads themselves. It is in mid-shaft, where the acceleration and deceleration may be made abnormal by bad driving, that the system has its greatest application, and apart from emergency conditions it is only when the driver tries to decelerate at a rate greater than that fixed by the system that the control exciter takes any share in the excitation of the main generator.

It will be seen, therefore, that the difficulties which Mr. Petch attributes to the use of Method (c) for controlling the generator field are non-existent. I agree that Method (a) is obviously the most satisfactory for decelerating at the end of the wind, and, as has been explained above, this has in no way been interfered with.

When emergency conditions are considered the problem immediately assumes a new aspect. To use Method (a) would involve complicated mechanical devices so that the cams would be able to operate at any point in the wind. Method (b), or a constant time for decelerating, irrespective of position in the shaft or of cage loads, is in my opinion fundamentally wrong. What time are we going to fix? We have a choice anywhere between two limits. The minimum time is that which will cause no injury to men riding in the cage and will avoid placing the limiting stress on the rope. The maximum time is that which, should an emergency trip occur at the point in the wind where the normal decelerating cam is coming into action, will bring the hoist to rest before the cage arrives at the overwind trips. Bearing in mind that in emergency the winder should be brought to rest as quickly as possible consistent with safety to men, ropes and machinery, if the maximum time is adopted with an emergency trip early in the wind where the winder motor is still motoring and has its full peak capacity for regenerative current available, and also the down-going rope is short with resulting high safety factor, then the winder is not being brought to rest as quickly as it might safely be. If however, the minimum limit of time is set,

then, should an emergency trip occur with a downgoing load near the end of the wind when the speed is high, the motor is already carrying a large amount of regenerative current, and the safety factor of the downgoing rope is approaching its minimum value, the consequences can be well imagined. The deceleration rate would be higher than would be safe for men in the cage; the motor would have to carry a current considerably in excess of its peak capacity, resulting almost certainly in flash-over and considerable damage to the brushes and commutator; and the rope would be overstressed. These effects would be considerably augmented with bi-cylindro-conical drums where the normal deceleration time at the end of the wind is divided into deceleration due to the scroll and final deceleration of the motor. I contend, therefore, that the decelerating time should be varied according to the position of the cages in the shaft, to compensate for the safety factor of the downgoing rope and for variations in cage load. In my system the first condition is governed by the control resistance (Fig. 4 in the paper) operated by the depth indicator. The second condition is governed by the cage loads themselves. I feel sure Mr. Petch will agree that these two methods of control are as simple as could be devised. Figs. 2 and 3 represent the rates of decay of the generator field current required to produce a constant retarding current for the two limits of time mentioned above, with the corresponding extremes of cage positions and cage loads.

As regards manœuvring with my system fitted, this again is a normal operation. Manœuvring seldom, if ever, requires armature currents of the order of normal accelerating currents, and, as in the case of deceleration, the system fixes the maximum accelerating current for any given position and load. Mr. Petch is not correct in his surmise that there is likely to be a delay in the building-up of this accelerating current; there is an almost immediate response to the movement of the driver's lever, the only delay being due to the inherent time-constant of the generator field system, which is of course normal and common to all machines.

I may add that the equipment has been in continuous service at Gifford's Shaft since February, 1938, and has given much satisfaction, particularly to the drivers.

In reply to Mr. Kirkwood, the standard accelerating and decelerating cams are still in service, for reasons explained in my replies to Mr. Bentley and Mr. Petch.

I agree with Mr. Kirkwood when he says that it would be better to initiate regenerative breaking immediately on failure of supply, and this particular emergency condition has been catered for on Gifford's winder since the paper was written. There is no doubt that with Ilgner sets a considerable amount of regenerative braking can often be accomplished before the speed of the fly-wheel reaches the limiting value. With straight Ward-Leonard sets, however, some means must be found for absorbing the regenerative energy immediately a trip occurs. I do not altogether like the idea of absorbing this energy in a resistor connected across the motor armature, as I have a rooted aversion to breaking the circuit between the generator and the motor. I would prefer to provide rheostatic braking on the driving motor of the convertor set.

P. F. ROWELL

SECRETARY OF THE INSTITUTION, 1909-1939

PERCY FITZ-PATRICK ROWELL was born in London on the 10th September, 1874, and was the son of the late Patrick Irvine Rowell, of Aberdeen. He received his early education at the Royal College of Mauritius, where he was awarded in 1893 the Gold Medal for Mathematics and a Leaving Scholarship. He subsequently studied mathematics and physics at Wren and Gurney's and at King's College, London. After spending a few years in the offices of two or three engineering firms, he left the British Thomson-Houston Co. on his appointment in 1901 as an assistant on the staff of The Institution. The late Mr. W. G. McMillan was at that time Secretary, and during his illness and subsequent to his death, Mr. Rowell was largely responsible for the administration of the office, until Mr. G. C. Lloyd's appointment in 1904 as Secretary. As a recognition of the efficient manner in which he carried out his duties the Council appointed him Assistant Secretary in April, 1904, and on Mr. Lloyd's resignation to take up the position of Secretary to the Iron and Steel Institute Mr. Rowell was appointed by the Council in February, 1909, to the secretaryship.

One of Mr. Rowell's first responsibilities as Secretary was the completion of the purchase of The Institution's present building, the alterations and improvements to the premises, and the transfer of the offices from 92 Victoria Street, Westminster. This transfer was effected in June, 1910, and the Lecture Theatre, Common Room and Library were ready for the opening meeting of the session 5 months later.

Consequent on the increased facilities due to The Institution's possessing a home of its own, a great expansion took place in its activities. One of the first matters to which Mr. Rowell had to give special attention was the improvement of the *Journal*, not only as regards more frequent and more prompt publication of the proceedings, but also the enlargement of the size from octavo to quarto. This change was made in December, 1913.

Mr. Rowell devoted his energies to the development of every aspect of The Institution's activities, and his success in achieving this was undoubtedly due primarily to his great tact, and to the friendly atmosphere always associated with his contacts with the membership. This was particularly in evidence on the occasion of his visits to the Local Centres and Sub-Centres, such visits being always looked forward to, not only by the local officers and Committees, but also by the members of each Centre. In his associations with engineers from kindred societies overseas and in The Institution's visits abroad his charm of manner and his knowledge of languages—particularly French and Italian—were a great asset. The cordial

relations which he created with electrical engineers in France through the Société Française des Électriciens were recognized in 1936 by the award of the Legion of Honour (Chevalier).

Among the landmarks in the development of The Institution during his secretaryship were the grant of the Royal Charter in 1921, the drafting of new Bye-laws, the Commemoration Meetings in 1922 to celebrate the Jubilee of the founding of The Institution, the Faraday Centenary Celebrations in 1931, and the proceedings resulting in the exemption of The Institution from income tax. The growth in the membership of The Institution during Mr. Rowell's service as Secretary was a striking feature of its progress, and was due in no small measure to his fostering influence. When he was appointed Secretary in 1909 the membership totalled about 6 000, and on his retirement last September this figure had increased more than threefold to over 19 000; in fact The Institution had become one of the largest scientific bodies in the world.

His organization of the office work and his attention to the smallest details resulted in the efficient conduct of all The Institution business and in the saving of time to members of Council and Committees. In fact the smooth running of all The Institution's meetings and social functions came to be accepted as a matter of course, and references to its clockwork precision became almost a regular feature of the speeches of retiring Presidents.

In the spring of 1928 he had a severe attack of pneumonia from the effects of which he never really recovered. His activities became more restricted and he gave up lawn tennis and badminton, on which he had always been keen, and devoted all his leisure to reading and chess. In the early days of broadcasting he took a great interest in wireless developments and constructed many sets himself. A few years ago he purchased a house at Weymouth, where he spent the majority of week-ends during the summer months, and he looked forward to his retirement there. Unfortunately his health was not strong enough to allow him more than a few months' enjoyment of his well-earned relaxation from the stress of office, and he passed away on the 14th April, 1940.

The sympathy of the membership will be extended to Mrs. Rowell, who always took such an active interest in those social functions of The Institution in which ladies could participate, and was a most welcome figure at such gatherings.

In addition to being Secretary of The Institution, Mr. Rowell was also a member, having been elected an Associate in 1913 and a Companion in 1929.

F. W. H.

PROCEEDINGS OF THE INSTITUTION

953RD ORDINARY MEETING, 8TH FEBRUARY, 1940

Mr. Johnstone Wright, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 25th January, 1940, were taken as read and were confirmed and signed.

The President announced that, during the month of January, 3 879 donations and subscriptions to the Benevolent Fund had been received, amounting to £1 845.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

A paper by Mr. H. H. Harrison, M.Eng., Member, entitled "Telegraphic Typesetting," was read and discussed. The paper was illustrated by a cinematograph film and a demonstration of apparatus.

A vote of thanks to the author, moved by the President, was carried with acclamation.

954TH ORDINARY MEETING, 22ND FEBRUARY, 1940

Mr. Johnstone Wright, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 8th February, 1940, were taken as read and were confirmed and signed.

The President referred to the loss which The Institution and the electrical engineering profession had suffered since the last meeting by the death of Col. R. E. B. Crompton, who had twice been President of The Institution and was an Honorary Member and Faraday Medallist, and he asked the members present to stand in silence for a few moments as a mark of respect.

Messrs. E. Stracey Cheel and A. R. Blakeley were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names

appeared on the lists (see page 311) had been duly elected and transferred.

The President announced that, as there would be no Electrical Engineers' Ball in 1940 the Benevolent Fund would suffer a loss of revenue of between £200 and £250; and he suggested that members who normally attend the Ball should send a special donation to the Fund in order to compensate for the loss.

A paper by Mr. H. L. Thomas, B.Sc.(Eng.), Associate Member, entitled "Insulation Stresses in Transformers, with special reference to Surges and Electrostatic Shielding," was read and discussed, and the author gave a demonstration of apparatus in connection with the paper.

A vote of thanks to the author, moved by the President, was carried with acclamation.

955TH ORDINARY MEETING, 7TH MARCH, 1940

Mr. Johnstone Wright, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 22nd February, 1940, were taken as read and were confirmed and signed.

The President announced that, during the month of February, 791 donations and subscriptions to the Benevolent Fund had been received, amounting to £300.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

A paper by Messrs. H. E. Cox and L. Drucquer, Associate Members, entitled "Oil-less Metalclad Switchgear for Medium-Voltage A.C. Circuits up to 660 Volts, Three-Phase," was read and discussed.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

956TH ORDINARY MEETING, 28TH MARCH, 1940

Mr. Johnstone Wright, President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 7th March, 1940, were taken as read and were confirmed and signed.

Messrs. H. M. Lacey and C. P. N. Rand were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on

the lists (see page 513) had been duly elected and transferred.

A paper by Messrs. B. G. Churcher, Member, and A. J. King, B.Sc.Tech., Associate Member, entitled "The Limitation of Transformer Noise," was read and discussed.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

INSTITUTION NOTES

THE LATE P. F. ROWELL

At the Ordinary Meeting of The Institution held on the 25th April the President stated that the members would have heard with deep regret of the death on the 14th April at Weymouth of Mr. P. F. Rowell, who retired from the secretaryship last September. He paid tribute to Mr. Rowell's services to The Institution and asked those present to stand in silence for a few moments as a mark of esteem.

In the Report of the Council for the year 1939-1940, presented at the Annual General Meeting held on the 9th May, reference is made to the retirement of Mr. Rowell after 38 years' service and to the presentation made to him by the President on behalf of the members. The Report will be published in the June issue of the *Journal*. An obituary notice will be found on page 506.

CONVERSAZIONE TO OVERSEAS MEMBERS AND MEMBERS SERVING IN H.M. FORCES

A Conversazione and Reunion of members from overseas and also of members serving in His Majesty's Forces is being arranged to take place in the Institution Building on Thursday evening, the 27th June, 1940.

Members from overseas who will be in England at the time of this Conversazione and would like to be present are asked to communicate with the Secretary immediately on their arrival, in order that invitations may be sent to them.

Similarly members serving in His Majesty's Forces who would be able to attend should inform the Secretary so that invitations can be sent to them.

HOOVER MEDAL

Mr. Gano Dunn, The Institution's Local Honorary Secretary for the U.S.A., has been awarded the Hoover Medal for 1939 at the Winter Convention of the American Institute of Electrical Engineers held in New York in January last. The Medal, which is one of the two highest honours available to American engineers (the other being the Edison Medal which had already been awarded to Mr. Gano Dunn), was in the joint award of the American I.E.E., the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers and the American Society of Mechanical Engineers.

BRITISH STANDARDS INSTITUTION

Dr. A. P. M. Fleming, C.B.E., M.Sc., has been nominated as one of the I.E.E. representatives for 1940-41 on the Engineering Divisional Council of the above Institution in place of Sir George Lee, O.B.E., M.C., who has completed the maximum permissible period of service. The other I.E.E. representatives on the Divisional Council are Dr. C. C. Paterson, O.B.E., and Sir Thomas Purves, O.B.E.

INTERNATIONAL ILLUMINATION COMMITTEE OF GREAT BRITAIN

Dr. C. C. Paterson, O.B.E., has been appointed by the Council to represent The Institution on the above Committee in place of the late Mr. H. W. Gregory.

I.E.E. MODEL FORM OF GENERAL CONDITIONS FOR CONTRACTS

In connection with Form A of the above Conditions (Home, with erection), revised 1938, the following additional clause was approved by the Council on the 28th March, 1940, for use during the present war:—

Price Adjustment.

If by reason of any rise or fall in the cost of material, labour, or transport or of conforming to such Acts, orders, regulations, and bye-laws as are first referred to in Clause 34 (Statutory and other Regulations) above or below such costs ruling at the date of the Tender the cost to the Contractor of performing his obligations under the Contract, shall be increased or reduced, the amount of such increase or reduction shall be added to or deducted from the Contract Price as the case may be Provided that no account shall be taken of any amount by which any cost incurred by the Contractor has been increased by the default or negligence of the Contractor.

ENGINEERING STUDENTS AND MILITARY SERVICE

The Council, impressed by the extreme national importance of preserving the flow of young trained electrical engineers for industry, for civilian capacities in the Defence Services, and for the technical branches of the Fighting Services, have for some time given earnest consideration to the steps which should be taken to attain this object. They have also considered the measures necessary to preserve an even distribution of those who have completed their academic training, in accordance with the requirements of industry and the Services.

In conjunction with The Institution of Mechanical Engineers, representations on the first of these correlated subjects were made to the Minister of Labour, who has recently issued the following Notice:—

"*Student Engineering Apprentices or learners*, are now reserved at the age of 18. This relates, however, only to a man employed in industry or under articles to a professional engineer who is certified by a university or technical institution or by a professional Institution of Engineers as within 2 years of the satisfactory completion of a course of study with a view to offering himself for the first time for (1) an engineering Degree; (2) an engineering Higher National Certificate; (3) the Associate Membership of the Institution of Civil, Mechanical or Electrical Engineers, or the Associate Fellowship of the Royal Aeronautical Society; or (4) an examination of similar standing to that of an engineering Degree.

"These amendments are not retrospective in their effect, that is they do not involve the release of men now in the Forces or of men who have already received enlistment notices."

The Council desire to draw the attention of those members who are responsible, either as employers or in an educational capacity, for the training of young engineers to the above Notice, which affects those Students of The Institution who come under one of the four categories enumerated. Such Students will now come within the Schedule of Reserved Occupations and need not make individual appeals if they desire to continue their studies and sit for one of the examinations specified before being called up. The Notice does not affect full-time university students whose cases are dealt with by the Joint Recruiting Boards which were set up on the outbreak of war.

In the active consideration of the second of the above subjects, namely the allocation of young engineers, a certain measure of agreement has already been reached and the Council hope shortly to be in a position to announce the nature of the new arrangements.

CENTRAL REGISTER OF NATIONAL SERVICE

It is desired to remind all members that The Institution continues to collaborate closely with the Ministry of Labour and National Service in the operation of the Central Register, in the compilation of which it has assisted in bringing forward the names of some 6 000 volunteers. In view of the increasing demands on certain groups of the Electrical Section it is hoped that all those who are in a position to volunteer and who have not yet done so will apply to the Secretary for a full description of the scheme and the necessary forms. It is possible that amongst those who have sent in their cards for record purposes only and who were not at that time in a position to volunteer, there may be some whose circumstances now allow them to volunteer for work of national importance.

Attention is particularly drawn to the letter which was issued to members in April, 1939, in which an outline is given of the machinery for the operation of the Register, and it is confirmed that the arrangements indicated in paragraphs (a) and (b) of that letter which are set out below are now in force.

(a) In war time, machinery will be set up to determine priority of work from the point of view of national importance, but members should not be deterred from offering their services because they are already under an obligation for other forms of National Service or are at present engaged on work regarded as of national importance.

(b) The selection of persons from the Central Register will be carried out with the advice of the Electrical Engineering Sub-Committee, which will advise such selection only if the services of a person already engaged on work of national importance are required for a post of greater national importance. No such selection will be made without advising the person's employer, if any, and the Sub-Committee will take account of any representations which may be made to it by such employer.

Members who have sent in their red cards for record purposes only, as well as those who volunteered and sent in both cards, are asked to assist in keeping The Institu-

tion's records up to date by informing the Secretary of any change in address or employment.

BRITISH STANDARDS

The Secretary has been asked by the British Standards Institution to draw attention to the following revised Specifications:—

Rubber Gloves for Electrical Purposes (B.S. No. 697).

A B.S. Specification for rubber gloves for electrical purposes was issued in 1936. As the result of experience gained in working to the Specification in this country and overseas, certain modifications were suggested, and a revised specification has now been published. The principal changes have as their object a clarification of the original wording, particularly as regards the interpretation of the mechanical tests. Numerous changes have been made in the appendices describing the methods of test, and in a few instances these changes have necessitated alteration of the limits in the Specification.

Copies of this revised Specification (B.S. No. 697—1940) can be obtained from the British Standards Institution, 28, Victoria Street, London, S.W.1, price 2s. each (2s. 2d. post free).

Trailing Cables for Mining Purposes (B.S. No. 708).

This Specification has recently been revised. The revision includes the addition of a section dealing with drill cables as well as some small modifications to the other sections, so that the specification now covers:—

- (1) Flexible trailing cables for use with coalcutters and similar purposes;
- (2) Pliable armoured trailing cables for use with conveyors, loaders, etc.; and
- (3) a section dealing with drill cables.

Copies of this revised Specification (B.S. No. 708—1940) can be obtained from the B.S.I., price 2s. each (2s. 2d. post free).

PROCEEDINGS OF THE WIRELESS SECTION

153RD MEETING OF THE WIRELESS SECTION, 7TH FEBRUARY, 1940

Dr. E. B. Moullin, M.A., Chairman of the Section, took the chair at 6 p.m. and, in his introductory remarks, mentioned that owing to the suspension of meetings of The Institution during the first half of the Session consequent upon the outbreak of war, this was the first meeting of the Section to be held this Session.

The minutes of the meeting held on the 3rd May, 1939, were taken as read and were confirmed and signed.

A paper by Mr. T. L. Eckersley, B.A., B.Sc., F.R.S., Member, entitled "Analysis of the Effect of Scattering in Radio Transmission," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

17TH INFORMAL MEETING OF THE WIRELESS SECTION, 27TH FEBRUARY, 1940

Dr. E. B. Moullin, M.A., took the chair at 6 p.m.

The minutes of the Informal Meeting held on the 14th March, 1939, were taken as read and were confirmed and signed.

A discussion, opened by Mr. O. S. Puckle, took place on "Time Bases and their Applications."

At the conclusion of the discussion a vote of thanks was accorded to Mr. Puckle for his introductory remarks.

154TH MEETING OF THE WIRELESS SECTION, 6TH MARCH, 1940

Dr. E. B. Moullin, M.A., took the chair at 6 p.m.

The minutes of the meeting held on the 7th February, 1940, were taken as read and were confirmed and signed.

A paper by Dr. T. Walmsley, B.Sc., Associate Member, entitled "Wire Broadcasting Investigations at Audio and Carrier Frequencies," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

PROCEEDINGS OF THE METER AND INSTRUMENT SECTION

88TH MEETING OF THE METER AND INSTRUMENT SECTION, 2ND FEBRUARY, 1940

Mr. F. E. J. Ockenden, Chairman of the Section, took the chair at 6 p.m. and, in his introductory remarks, referred to the fact that on account of the suspension of meetings of The Institution during the first half of the Session consequent upon the outbreak of war, this was the first meeting of the Section to be held this Session.

The minutes of the meeting held on the 5th May, 1939, were taken as read and were confirmed and signed.

A paper by Mr. J. R. Brookman, M.E., Member, entitled "Maintenance of Relays and Associated Equipment," was presented by Mr. F. J. Lane, M.Sc., on behalf of the author, and was read and discussed.

A vote of thanks to Mr. Lane and to the author, moved by the Chairman, was carried with acclamation.

89TH MEETING OF THE METER AND INSTRUMENT SECTION, 1ST MARCH, 1940

Mr. F. E. J. Ockenden, Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 2nd February, 1940, were taken as read and were confirmed and signed.

A paper by Messrs. F. O. Morrell, B.Sc., Associate Member, and the late G. R. Oman, B.Sc., entitled "A Method of Measuring and Recording the Frequency Error of Alternating-Current Power Supplies," was read and discussed.

A vote of thanks to Mr. Morrell, moved by the Chairman, was carried with acclamation.

A demonstration of the principles of the quartz-crystal clock was then given by Mr. L. Essen of the National Physical Laboratory. On the motion of the Chairman a vote of thanks was accorded to Mr. Essen.

PROCEEDINGS OF THE TRANSMISSION SECTION

36TH MEETING OF THE TRANSMISSION SECTION, 14TH FEBRUARY, 1940

Mr. F. W. Purse, Chairman of the Section, took the chair at 6 p.m. and, in his introductory remarks, stated that, on account of the suspension of meetings of The Institution during the first half of the Session consequent upon the outbreak of war, this was the first meeting of the Section to be held this Session.

The minutes of the meeting held on the 10th May, 1939, were taken as read and were confirmed and signed.

A paper by Messrs. E. Fawcett, Member, H. W. Grimmitt, Associate Member, G. F. Shotton, Member, and H. G. Taylor, M.Sc.(Eng.), Associate Member, entitled "Practical Aspects of Earthing," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

37TH MEETING OF THE TRANSMISSION SECTION, 13TH MARCH, 1940

Mr. F. W. Purse, Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 14th February, 1940, were taken as read and were confirmed and signed.

A paper by Mr. S. W. Melsom, Member, entitled "Electric Cables and Fire Risks: Recent Developments and Investigations," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

ROLL OF HONOUR (FIRST LIST)

The following members have lost their lives in the service of their country:—

Killed in Action.

Meredith, Sub-	Royal Naval Reserve	Graduate
Lieut. E. G.		

Killed on Active Service.

Taylor, Pilot Officer	Royal Air Force	Graduate
G. S., B.A.		
Warren, Flying	Royal Air Force	Student
Officer J. H.		

HONOURS AWARDED TO MEMBERS SERVING WITH H.M. FORCES (FIRST LIST)

Distinguished Service Order.

Daniel, Captain	Royal Navy	Associate
C. S.		Member

PROMOTIONS AND TRANSFERS OF MEMBERS ON SERVICE WITH H.M. FORCES (SECOND LIST)*

Name	Corps, etc.	Rank
de Burgh, D. H.	Royal Air Force	Group Captain
Reading, J.	Royal Signals	Major
Sproull, A. W.	Royal Engineers	Colonel

Associate Members

Brewis, J. M.	Royal Army Ordnance Corps	Lieut.-Col.
Coates, T.	Royal Naval Volunteer Reserve	Lieutenant
Isaac, F. C.	Royal Navy	Lieutenant
Pitcairn, A. C.	Royal Signals	Captain
Rees, T.	Royal Naval Volunteer Reserve	Lieutenant
Sadler, E. H.	Royal Army Ordnance Corps	Major
Thurner, W. M. F.	Royal Artillery	Sec. Lieut.

* See page 311.

Associates

Name	Corps, etc.	Rank
Robertson, L. R.	Royal Navy	Lieutenant
Walton, E. S.	Auxiliary Military Pioneer Corps	Sec. Lieut.

Graduates

Baker, M. W.	Officer Cadet Training Unit	Cadet
Balean, H. H.	Royal Naval Volunteer Reserve	Lieutenant
Beazley, B. S.	Royal Engineers	Sec. Lieut.
Brand, N. F.	Royal Tank Regiment	Sergeant
Castellan, G. E.	Royal Engineers	Sergeant
Crow, D. R.	Officer Cadet Training Unit	Cadet
Lavarack, T. V.	Royal Naval Volunteer Reserve	Lieutenant
Martin, C. T.	Royal Naval Volunteer Reserve	Lieutenant
Meikle, J. C.	Royal Army Ordnance Corps	Major
Metcalf, A. B.	Royal Naval Volunteer Reserve	Lieutenant
Perry, W. H.	Royal Army Ordnance Corps	Lieutenant
Pillinger, E. W.	Royal Naval Volunteer Reserve	Lieutenant
Richardson, R. F.	Officer Cadet Training Unit	Cadet

Students

Owen, G. R.	Officer Cadet Training Unit	Cadet
Stewart, A. C.	Royal Naval Volunteer Reserve	Sub-Lieut.

**MEMBERS ON SERVICE WITH H.M. FORCES
(FOURTH LIST)***

(NOTE.—The Secretary will be glad to receive, for publication in subsequent lists, the names of other members of The Institution who are serving with His Majesty's Forces, together with particulars of their rank and the unit in which they are serving.

A Roll of Honour, and lists of honours awarded, promotions, transfers, etc., are also being published.† All such particulars, both in regard to a member himself and in connection with other members of whom he may have knowledge, should be sent to the Secretary as early as possible so that the Institution records can be kept up to date.)

Members

Name	Corps, etc.	Rank
Bowen, W. O.	Royal Signals	Major
Burns, S.	Royal Army Ordnance Corps	Major
Ewer, G. G.	South African Defence Headquarters	Lt.-Col.
im Thurn, J. K.	Royal Navy	Vice-Admiral
Leishman, G. A. B.	Royal Artillery	Major
McLare, J. P.	Royal Army Ordnance Corps	Lt.-Col.
Milliken, R. C.	Brigade Commander	Brigadier
Sparks, A. C.	Royal Engineers	Staff Captain
Thorpe, D. W.	County of London Yeomanry	Captain
Watson, E. C.	Royal Navy	Captain
Wilson, W. P.	Royal Air Force (V.R.)	Squadron Leader

Associate Members

Name	Corps, etc.	Rank
Anderson, C.	Royal Army Ordnance Corps	Lieutenant
Barrett, H. E.	Royal Naval Volunteer Reserve	Sub-Lieut.
Berry, H. W.	Royal Australian Air Force	Squadron Leader
Bradley, J. K.	Royal Army Ordnance Corps	Lieutenant
Carter, E. T. G.	Royal Engineers	Lt.-Col.
Chapple, H. J. B.	Royal Air Force (V.R.)	Flt.-Lieut.
Chapple, S. H.	Royal Army Ordnance Corps	Lieutenant
Coates, W. H. R. A.	Royal Air Force (V.R.)	Flt.-Lieut.
Collings, J. L.	Royal Signals	Captain
Henry, H. G.	Royal Army Ordnance Corps	Lieutenant
Hunter, E. I.	Royal Signals	Lieutenant
Jacobs, P. G.	Royal Signals	Lieutenant
Lauderdale, F. S.	Royal Signals	Sec. Lieut.
Lester, G. C. O.	Royal Naval Volunteer Reserve	Sub-Lieut.
MacKenzie, M.	Royal Army Ordnance Corps	Lieutenant
Martin, A. G.	Royal Artillery	Captain
Murray, W. J. A.	Madras Sappers and Miners	Sec. Lieut.
Polden, C. J.	Royal Air Force	Squadron Leader
Roberts, L. C.	Royal Engineers	Lance-Corporal
Rogers, W. H. G.	Royal Signals	Lt.-Col.
Ross, J. D.	Royal Artillery	Captain
Rycroft, D. M.	Royal Engineers	Major
Simon, R. H. S.	Royal Signals	Sec. Lieut.
Stack, E. F. R.	Royal Engineers	Captain
Stebbing, G. C.	Royal Engineers	Sec. Lieut.
Surfleet, W. A.	Royal Army Ordnance Corps	Lieutenant
Tamplin, S. R.	Royal Engineers	Sec. Lieut.
Taylor, L. N.	Royal Engineers	Captain
Teal, A. E.	Royal Engineers	Lieutenant
Vinten-Fenton, C. V.	Royal Engineers	Sec. Lieut.

Companion

De Roemer, C. W.	Royal Army Ordnance Corps	Major
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Associates

Chapman, L. J.	Royal Army Service Corps	Captain
Rowan, A. W.	Royal Naval Volunteer Reserve	Sub-Lieut.

Graduates

Alexander, J. F.	Royal Air Force	Sergeant
Anstey, F. B.	Officer Cadet Training Unit	Cadet
Ashworth, H.	Royal Naval Volunteer Reserve	Sub-Lieut.
Bamberry, C. M.	Royal Naval Volunteer Reserve	Sub-Lieut.
Blackley, V. K.	Royal Air Force	Sergeant
Brodrick, A. G.	Royal Signals	Signalman
Brown, T. T.	Royal Air Force	Pilot Officer
Butterworth, A.	Royal Air Force	A.C.2
Bywater, K. A. V.	Officer Cadet Training Unit	Cadet
Cramb, A. L.	Royal Naval Volunteer Reserve	Sub-Lieut.
Euler, H. L.	Royal Naval Volunteer Reserve	Lieutenant
Evans, G. E.	Royal Naval Volunteer Reserve	Sub-Lieut.

* See *Journal I.E.E.*, 85, p. 653, and 86, pp. 99 and 308. † See page 510.

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Fell, P. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Forster, P. C. T.	Royal Air Force	Sergeant
Freeland, J. A. D.	Royal Naval Volunteer Reserve	Sub-Lieut.
Garrett, R. G. W.	Royal Engineers	Sec. Lieut.
Gilchrist, S.	Royal Naval Volunteer Reserve	Sub-Lieut. (E.)
Green, C.	Royal Signals	Sec. Lieut.
Hampton, D. A.	Royal Air Force	Sgt. Pilot
Harris, J.	Royal Army Ordnance Corps	Lieutenant
Hawkins, H. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Hill, J. N.	Royal Engineers	Sec. Lieut.
Hindle, H.	Royal Army Ordnance Corps	Private
Holbrook, G. W.	Officer Cadet Training Unit	Cadet
Howe, R. L.	Royal Signals	Sergeant
Ireland, G. D.	Royal Artillery	Major
Jack, D. M.	Royal Air Force (V.R.)	Pilot Officer
Jackson, A. E.	Royal Armoured Corps	Trooper
Kendall, M. W.	Royal Army Ordnance Corps	Major
Kenner, J. W.	Royal Air Force	Sergeant
Knox, J.	Royal Signals	Captain
Larsen, P. W.	Royal Engineers	Sec. Lieut.
Lea, C. A.	Royal Air Force (V.R.)	A.C.2.
Lees, J. R.	Royal Engineers	Sec. Lieut.
Lowery, G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Mackenzie, D. H. A.	Royal Army Ordnance Corps	Lieutenant
Mason, T. F. V.	Royal Army Ordnance Corps	Lieutenant
Montgomery, D.	Royal Army Ordnance Corps	Lieutenant
Morgan, H. G. B.	Royal Naval Volunteer Reserve	Sub-Lieut.
Munton, R. D.	Royal Army Ordnance Corps	Private
Newbigging, I. B.	Royal Air Force	Squadron Leader
Newby, T. H.	Royal Engineers	Sec. Lieut.
Newman, D. F. W.	Officer Cadet Training Unit	Cadet
Pattenden, R. E.	Royal Naval Volunteer Reserve	Sub-Lieut.
Perry, P. C. A.	Royal Engineers	Sec. Lieut.
Phillips, H. M. B.	Royal Army Ordnance Corps	Lieutenant
Pipkin, C. H. B.	Royal Army Ordnance Corps	Lieutenant
Prickett, V. C. R.	Royal Artillery	Gunner
Purcell, G. S.	Royal Army Ordnance Corps	Lieutenant
Reed, J. A.	Indian Army Ordnance Corps	Sec. Lieut.
Rogers, N. S.	Royal Engineers	Sec. Lieut.
Sandercock, K. N.	Royal Engineers	Cadet
Sandys, G. E.	Royal Army Ordnance Corps	Lieutenant
Sims, E. A.	Royal Naval Volunteer Reserve	Lieutenant
Smith, L. H. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Smith, P. E. C.	Royal Signals	Lieutenant
Somerville, R. D.	Royal Engineers	Sec. Lieut.
Stephenson, T. G.	Royal Signals	Sec. Lieut.
Streatfield, E. C.	Royal Signals	Signalman
Suttle, C. E. P.	Royal Air Force	Flt.-Lieut.
Swinney, E.	Royal Air Force	Warrant Officer
Tuttielt, L. A.	Royal Naval Volunteer Reserve	Sub-Lieut.
Warne, G. H.	Royal Naval Volunteer Reserve	Lieutenant
Webster, E. A.	Royal Signals	Signalman

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Widdowson, J. O.	Royal Army Ordnance Corps	Lieutenant
Winton, R. C.	Royal Army Ordnance Corps	Lieutenant
Wooster, C. B.	Indian Divisional Signals	Sec. Lieut.
Wylie, J. H.	Royal Artillery	Gunner

Students

Bagshaw, A. S.	Royal Naval Volunteer Reserve	Sub-Lieut. (E.)
Bainbridge, T. R.	Royal Air Force	A.C.2
Barr-Wells, D. R.	Royal Artillery	Gunner
Bishop, R. G.	Royal Engineers	Corporal
Bottomley, W. D.	Royal Air Force	A.C.2
Bradford, J. P.	Royal Army Ordnance Corps	Private
Chipperfield, V. J.	Royal Air Force (V.R.)	Pilot Officer
Clark, F. W. J.	Royal Artillery	Gunner
Collard, J. G.	Middlesex Regt.	Lance-Corporal
Cooper, R. A.	Officer Cadet Training Unit	Cadet
Cosgrave, S. T.	Royal Signals	Lance-Corporal
Curtis, G. D.	Royal Signals	Sec. Lieut.
Dain, C.	Royal Army Ordnance Corps	Staff Sergeant
Edwards, D. G.	Royal Naval Volunteer Reserve	Sub-Lieut. (E.)
Espir, J. R. F.	Royal Signals	Lance-Corporal
Ferguson, S. G.	Royal Engineers	Sapper
Ferrer, G. W.	Royal Engineers	Sapper
FitzGerald, G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Ford-Hutchinson, P. W. S.	Royal Engineers	Sapper
Gibson, H. P.	Royal Tank Regiment	Trooper
Gordon-Wright, J. G.	Royal Signals	Sec. Lieut.
Gray, C. K.	Royal Air Force	Sergeant
Griffiths, R. K.	Honourable Artillery Company	Gunner
Harrison, D.	Royal Signals	Signalman
Higson, H. W.	Officer Cadet Training Unit	Cadet
Hoare, G. F.	Fleet Air Arm (R.N.)	Electrical Fitter
Horowitz, T.	Royal Engineers	Sapper
Hurley, J. J.	Royal Naval Volunteer Reserve	Lieutenant
Isted, C. R.	Royal Air Force	A.C.2
Jakeman, F. R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Job, J. V. E.	Officer Cadet Training Unit	Cadet
Johnson, B. K.	Royal Army Service Corps	Private
Johnson, J. K., jun.	Royal Naval Volunteer Reserve	Sub-Lieut.
Jones, G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Laidlaw, D. W.	Royal Navy	Sub-Lieut.
Laplough, J. S.	Royal Air Force	Sgt. Pilot
Lees, E. J.	Royal Engineers	Sapper
Lefaux, G. S.	Royal Artillery	Private
Leonard, C. A. W.	Royal Army Service Corps	Private
Meggs, R. S.	Rifle Brigade	Rifleman
Miles, W. G. D.	Royal Air Force (V.R.)	A.C.2
Moloney, J. L. H.	Royal Artillery	Gunner
Moody, P. H.	Royal Signals	Sec. Lieut.
Ness, R. H.	Royal Signals	Signalman
North, C. A.	East Surrey Regt.	Private
Norton, E. R.	Berkshire Regt.	Sec. Lieut.
O'Connor, J. R. W.	Royal Army Ordnance Corps	Private
Parke, E. G.	Royal Signals	Signalman
Paul, J. M.	Royal Artillery	Sec. Lieut.
Powell, E. B.	Royal Air Force	A.C.2

<i>Name</i>	<i>Corps, etc.</i>	<i>Rank</i>
Priest, F. I. D.	Royal Army Ordnance Corps	Lieutenant
Roach, W., jun.	Royal Artillery	Lance-Sergeant
Rushforth, H.	Royal Air Force	A.C.2
Scattergood, G. E.	Royal Signals	Signalman
Scott, G. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Seckham, C. C.	Royal Engineers	Sapper
Sheard, J. R.	Royal Air Force	Leading Aircraftman
Shearer, A. E.	Royal Signals	Signalman
Sheedy, J. R.	Royal Signals	Signalman
Spratt, J. H.	Suffolk Regt.	Sec. Lieut.
Starnes, H. W.	Royal Artillery	Gunner
Thompson, G. P.	Royal Artillery	Gunner
Trapnell, A. H.	Royal Army Ordnance Corps	Private
Tyack, D. R.	Royal Army Ordnance Corps	A/Lance-Corporal
Venn, M. E. R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Wade, W. R.	Officer Cadet Training Unit	Cadet
Webb, G. F. H.	Royal Air Force	Pilot Officer
Westbrook, H. W.	Royal Signals	Signalman
Wills, R. J.	Royal Artillery	Sec. Lieut.
Winder, E. M.	Royal Tank Regiment	Trooper
Wright, A. H.	Royal Navy	Electrical Artificer Petty Officer

ASSOCIATE MEMBERSHIP EXAMINATION: NOVEMBER, 1939 (OVERSEAS CENTRES)

LIST OF SUCCESSFUL CANDIDATES WHO SAT IN AUSTRALIA, CEYLON, FEDERATED MALAY STATES, NEW ZEALAND AND SHANGHAI

[Success in this Examination does not of itself constitute the candidate an Associate Member.]

Parts I and II*

Allen, Carrol (*New Zealand*).
 Barraclough, John Francis (*F.M.S.*).
 Chandrasinghe, Don Paul (*Ceylon*).
 Downey, Raymond Sinclair (*Victoria, Australia*).
 Easton, Hone Iveson (*New Zealand*).
 Emms, Arthur George (*New Zealand*).
 Francis, Edward Charles (*New South Wales*).
 Geoghegan, Joseph Francis (*New Zealand*).
 Graham, Joseph William (*New Zealand*).
 McIndoe, William Arthur (*New Zealand*).
 Maunder, Augustine Hamilton (*New Zealand*).
 Nixon, John Roger (*New Zealand*).
 Pyke, Stephen (*Victoria, Australia*).
 Reynolds, Sydney McGregor (*New Zealand*).
 Self, Percy Noel (*New South Wales*).
 Tokmakoff, Wladimir Veniamin (*Shanghai*).
 Williams, Thomas (*New Zealand*).
 Wilson, James (*Victoria, Australia*).

Part I only

Lovegrove, Richard Harris (*New South Wales*).
 Millard, Harold Wilfred (*New Zealand*).
 Monk, Richard Read (*Perth, Western Australia*).

* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Part II only

Barth, Arthur Harold (*New Zealand*).
 Blakeley, Wilfred John (*New Zealand*).
 Brown, William Henry (*New Zealand*).
 Gomes, George Dominic (*F.M.S.*).
 Ramsay, Walter (*New Zealand*).

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 28th March, 1940, the following elections and transfers were effected:—

Elections

Associate Members

Boyd, John Malcolm, B.Sc. (Eng.).	Khosla, Som Nath, B.Sc. (Eng.).
Chapple, Sydney Harold.	Lawrence, Cyril William, B.Sc.(Eng.).
Cockburn, Robert, M.Sc., Ph.D.	Petri, Ronald David.
Coombes, John Eric M., B.Sc.(Eng.).	Spencer, Harold Hildred.
Craig, William Macderment, B.Sc.(Eng.).	Spencer, Wilfred Joyce.
Flanagan, William John C.	Stanbury, Harry Clifford O., B.Sc.(Eng.).
Gallagher, Charles, B.Sc. (Eng.).	Walmsley, Arthur Reginald.
Greef, Gabriel Jan S.	Warhurst, Frank.
Holland, Herbert Roberts.	Williams, Robert Vernon C.

Associates

Currie, Russell Mackenzie.	Tait, William McDiarmid.
Mendham, Clement Hugh.	Walsh, John.
Rowan, Alexander William.	

Graduates

Bartlett, Colin Peter, B.Sc.	Lorraine, Thomas Edward.
Beard, Arthur James, B.Sc.	McLeod, Allan James.
Burn, Andrew Alexander.	Marchant, Henry John, B.Sc.
Cox, Frederick Walter.	O'Seaghda, Fionnbarra, B.E., B.Sc.(Tech).
Darby, John Kinton, B.Sc.	Partington, George Frank
Edgar, Hamish.	Pemberton, Max Eric.
Edywean, Ronald Murton.	Ritchie, Robert William, B.Sc.
Gillett, Anthony Walter, B.A.	Siggs, Eric Milne.
Griffiths, William Frederick, B.Sc.(Eng.).	Yuen, Shao-Tang, B.Sc.
Holloway, James Cloudesley.	

Students

Anderson, Alexander.	Basu, Rabindra Kumar, B.Sc.
Asher, Naretam Vallabhdas.	Bennett, Thomas John.
Bailey, Eric.	Bhide, Jagannath Mahadeo, B.Sc.
Bailey, Leslie.	Bishop, Derrick Malcolm.
Bal, Dattatraya Vishnu.	Brown, Wallace.
Banks, Eric.	Brown, William Alexander.
Barlow, James Frank.	Burton, Alan John H.
Barlow, John.	Butter, Stanley.
Barr, Harry Norman.	

Students—continued.

Butterworth, Robert.	May, Reginald John.
Carlow, William Dean.	Medlock, Reginald Stuart,
Chakravarti, Sukhamay.	B.Sc.
Chalmers, David Gibson.	Nair, K. Ramakrishnan.
Chambers, Kenneth Douglas.	Nanavati, Sagunrai Dilsukhrui, B.E.
Claase, Jacob Jesaja.	Nene, Ramchandra Ganesh.
Coughtrie, George Thomas.	Nicholson, Norman.
Court, Gwyn William G., B.Sc.	Nobbs, Harold.
Elias, Thomas Gwyn.	Ord, Ian.
Elliott, Joseph Merelie.	Osmond, George Cecil.
Elsden, Robert Alan.	Paice, Max Raymond G.
Emerson, Eric.	Palmer, John Osmond M.
Emery, Frank Albert.	Payne, Ronald Arthur.
Farmer, Ernest.	Pool, Stanley Donald.
Filby, Eric George.	Priestley, Eric Holden.
Fletcher, Ronald.	Prowse, Ronald James.
Fogg, James.	Quayle, Ernest.
Froom, Jocelyn.	Rastogi, Satya Prakash.
Froud, George.	Reddish, Wilson.
Gadenne, Douglas Charles.	Robinson, Geoffrey Thomas G.
Gaskell, Norman.	Rogers, Patrick Sutherland.
Gibson, Robert McGregor.	Rowe, James Hunter.
Gillespie, Arthur Blackley.	Sabaratnam, Ponniah.
Good, Walter Robert C.	Sadler, Peter.
Gordon, Ian Humphry.	Sinha, Dwijendra Narayan, B.Sc.
Gray, Reginald Irvan.	Smith, Denys Sydney.
Halbe, Dhundiraj Narayan, B.E.	Smith, Ronald Buckley.
Hardy, Denis Raymond.	Southern, Alan Worrall.
Hartley, Kenneth Alison.	Speight, Alec.
Hatfield, Geoffrey Herbert.	Spratt, James Henry.
Heesom, Sydney Denis.	Stabb, Thomas George.
Heys, Cyril.	Subramanian, R. T., B.Sc.
Holme, John Lawrence.	Sutton, Harry Eugene, B.Sc.
House, Frederick Charles.	Taylor, Cecil Richard.
Howells, Myrddin Price.	Tebby, Denis Edward R.
Hughes, Geoffrey James.	Thomas, Glyn Burton S.
Humber, Alfred John.	Todd, William Milton.
Hunt, Derek.	Toyne, Clifford Clarke.
Johnson, Philip Arnold.	Tyrer, Donald Neville.
Khan, Mir Ahmed H., B.Sc.	Uren, John.
King, Matthew Hamilton.	Walker, Sydney Herbert.
Langham, Eric Miles.	Warburton, Philip
Lavingia, Parmanand Popatlal.	Watkins, Thomas Brown.
Law, George.	Whetton, Denis Stanley.
Leaney, Ronald Herbert.	Whitelegg, James William.
Lee, Kenneth Francis W.	Wolstenholme, Arthur Scott.
Ludlam, John Thomas.	Wootton, Leonard Wilfred.
Maciver, John Craven.	Worsnop, Walter.
Maclese, Arthur.	Zahler, Gunter.
Marshall, Howard Beckwith.	

Transfers*Associate Member to Member*

Dawe, Frank Walter.	Hughes, Charles Wesley, B.Sc.
Dunn, Philip Ryland, B.Sc.	Jago, Ronald Albert.
Gurney, Frank,	

Associate Member to Member—continued.

Pick, Thomas Sisson, B.Sc.	Wilton, Donald Victor.
Saunders, Norman Frank T., B.Sc.	Winch, Gordon Thomas.

Associate to Associate Member

Booth, Clifford.
Nettleton, William Edward B.
Pound, Edwin Thomas.

Graduate to Associate Member

Bhardwaj, Diwan Chand, B.Sc.(Eng.).	Lowne, Hugh Reginald B.
Birrell, Robert Cuthbertson.	Luff, Arnold George H.
Blake, Kenneth Balfour, B.Sc.(Eng.).	Morris, Harry.
Bland, Frank Edward, B.Sc.(Eng.).	Needham, Arthur Wheel-don.
Borgars, Sydney John, B.Sc.(Eng.).	New, Charles Morley.
Brierley, Frank.	Oley, Frances William.
Clark, William Henry V., B.Sc.(Eng.).	Palmer, Arthur Montague F.
Daniels, James Denis, B.Eng.	Parker, Stanley Horace.
Esson, George.	Pizzey, James Herbert.
Farrall, Robert.	Richards, George Trevor.
Follenfant, John Lindsay.	Schulthess, Frank von.
Glyde, Thomas Charles W.	Shiva, Abol Qassem, B.Sc.
Haigh, Albert Edward.	Simpson, Ronald Mawson O.
Hamilton, James Lawrie.	Smith, Robert Main A., B.Sc.(Eng.).
Hammond, John Durell Le B.	Stevenson, Jacob.
Harrop, Thomas Gordon C.	Thomas, Geoffrey Mosley, B.A.
Harvey, Arthur Frank, D.Phil., B.Sc.(Eng.).	Walker, George Edward.
Johnston, Andrew Brown, B.Sc.	Watson, Daniel Stewart, B.Sc.(Eng.).
Jones, David Evered H., M.Sc.	White, Harry William.
	Whitehead, Edward Daniell, B.Sc.
	Whitfield, John Nelstrop, B.Sc.(Tech.).

Student to Associate Member

Peat, John Dewar, B.Eng.

Student to Associate

Kilpin, John Cecil.
Wilkins, Sydney Rutherford.

At the Ordinary Meeting of The Institution held on the 25th April, 1940, the following elections and transfers were effected:—

Elections*Associate Members*

Allen, Carrol.	Shaw, Cyril Edmund.
Angier, Norman Douglas, B.Sc.	Stafford, Leslie Joseph.
Ash, Horace William, B.Sc. (Eng.).	Tsirimokos, Alcibiade, B.Sc.
Mulligan, John Wesley.	Urquhart, James Fenton, B.Sc.
Munro, Hugh.	Williams, Vernon Eustace.
Nissim, Raoul, D.Eng.	Wyke, Philip Neil, B.Sc.
Pulham, George Brook,	

Associates

Barnes, Victor Frederick W. Holmes, Robert Gerlan D.
Hall, Stanley. Hunter, James Laird.

Graduates

Bhat, Gurple Srinivas, Palmer, Frank Henry
B.Sc.(Eng.). George.
Bose, Rabindra Kumar, Poacha, Savak Framroze,
B.Sc. B.Sc.
Caldwell, James. Pragasam, Arthur Balraj,
Clarke, Roger Cecil. B.Sc.(Eng.).
Das, Styendra Prasanna, Ryder, Ernest James,
B.E. M.Sc., B.Sc.
Davis, Lewis George. Seshachar, Kolar Venkata,
Ghai, Manohar Lal. B.Sc.
Halliygey, Frederick Sharan, Swami, M.Sc.
Joseph. Shrotri, Bhalchandra Mu-
Hancock, George Norman. kund.
Jain, Uggar Sain, B.A., Smail, Thomas.
B.Sc.(Eng.). Smith, Ernest Leslie.
Kaka, Burjor Jehangirjee. Srinivasiengar, Kadaba
Kar, Balai Chandra, M.Sc. Rangiangar, M.Sc.
Kesava Rao, Mysore Van- Struthers, Michael, B.Sc.
katasubharao, B.Sc. Wadhvani, Pokardas Chu-
Lahiri, Biswanath. hardas, B.Sc.(Eng.).

Students

Agrawal, Ramesh Chan- Long, William Joseph.
dra. Lynn, John Williamson.
Athavale, Aravind Nara- Mahomed, Rovshen G.
yan. Maleksirat, Hassan.
Aziz ud Din, C., B.A. Mills, Vincent George H.
Basu, Mihir Kumar, Mir Baghi, Abdul Rassoul.
B.Sc. Modak, Vasant Narayan.
Bennett, Bryant Roy. Mukherjee, Ajitendra,
Bimbhat, Gurcharn Singh, B.Sc., M.Sc.
B.Sc. Mukhopadhyaya, Ram
Bubb, Eric Lawrence. Ranjan, M.Sc.
Buckley, Stanley James. Murghai, Baldev Singh,
Cannon, John. B.A.
Chapman, John. Murphy, Dennis.
Chari, Satuluri Sree Ven- Pershad, Kanaya.
kate. Phillips, William.
Cummins, Eric George. Piper, Norman Leslie.
Datta, Budh Dev. Rananaware, Dattajirao
Dayal, Parankusam Dina. Shankarrao.
Devasirvatham, Devana- Rhodes, William Derek.
son Abraham. Robinson, Richard Hugh
Gandhi, Vadilal Maganlal. S.
Garuda Char, Mallur Sriniva- Sahay, Damoder Nath.
vasa S. Schaaning, Per Anthony.
Gopalaswamy, Satulury. Sen, Bansilal, B.Sc.
Governor, Jamshedji Sharma, Tilak Raj.
Erachshaw. Sharp, Bernard Frederick.
Gupta, Lal Chand. Singh, Mohindar.
Hill, Barrington Charles. Spring, Alfred Laurence.
Hunt, Albert. Statham, Ernest John.
Jackson, Peter. Thaker, Ramashanker.
Jain, Kailash Chandra, Trayler, Philip Arthur.
M.Sc. Tyagi, Param Singh.
Kemp, Walter Derrick. Vadehra, Gorakh Nath,
Knight, Eric Dawson. M.Sc.

Students—continued.

Venkatakrishnan, A. S. Whittaker, James Ains-
Verma, Badri Narain. worth.
Walton, Harry Roebuck. Wye, William George H.

*Transfers**Associate Member to Member*

Beasant, Henry Rainforth. Lees, John Brearley.
Dennis, Reginald Burton, Lingard, Harold.
B.Sc.(Eng.). Walmsley, Thomas, B.Sc.
Goldup, Thomas Edward. Watson, George Oliphant.

Associate to Associate Member

Hobson, Robert John. Rose, Arthur Harold W.
Miller, Norrell Herbert. Wilson, James.

Graduate to Associate Member

Ashmawy, Sayed Ahmad. Hole, Francis Cuthbert.
Bell, David Arthur, M.A., Hopkinson, Ralph Gal-
B.Sc. braith, B.Sc.(Eng.).
Botting, Ernest Leopold, Longhorn, James Henry.
B.A., Major, R.E. Lowther, Gilbert.
Bowen, Thomas Henry, Makaroff, Igor, B.Sc.(Eng.).
B.Sc.(Eng.). Marshall, David Samuel,
Cape, Maxwell. B.Sc.
Carpenter, Harry. Palfrey, Harold Charles.
Carter, William Hutton, Parker, Ronald.
B.Sc. Parsons, Arthur James.
Cattle, Edward Arthur. Picken, Francis William.
Cockram, Reginald Wil- Rustin, Maurice Edward.
liam J. Sandiford, Kenneth Rod-
David, Ronald Paul, B.Sc. ford, B.Sc.(Eng.).
Garth, Herbert Leslie. Southgate, Arthur.
Gilchrist, James. Straughan, Alan Robert.
Gillies, Arthur Julian. Tait, James Sharp, B.Sc.
Glover, Roy Phillips, B.Sc. (Eng.).
(Eng.). Taylor, Charles Henry.
Gregory, Henry James. Westcott, Nicholas.
Gresty, Ernest, B.Sc. Wild, John Antony.
(Tech.). Wimpenny, Norman.

Student to Associate Member

Barwick, Emerson Clarke, B.Sc.(Eng.).
Wilen, James Allan.

The following transfers were also effected by the Council at their meeting held on the 11th April, 1940:—

Student to Graduate

Balasubramanian, Musiri Cockburn, Andrew Stod-
Doraiswamy, B.A. dart.
Bell, Alfred Eric, B.Sc. Cook, Thomas James.
(Eng.). Cooper, Geoffrey Ernest F.
Benson, Cyril. Cousins, Norman James.
Bernard, Geoffrey George, Dandekar, Chintaman Da-
B.Sc.(Eng.). madar.
Brown, Thomas. De, Swayambho Kumar.
Butler, Charles George. Foot, James.
Chappel, Mervyn Joseph Foulds, Henry Charles G.
W. Fuchs, Alfred Robert.

Student to Graduate—continued.

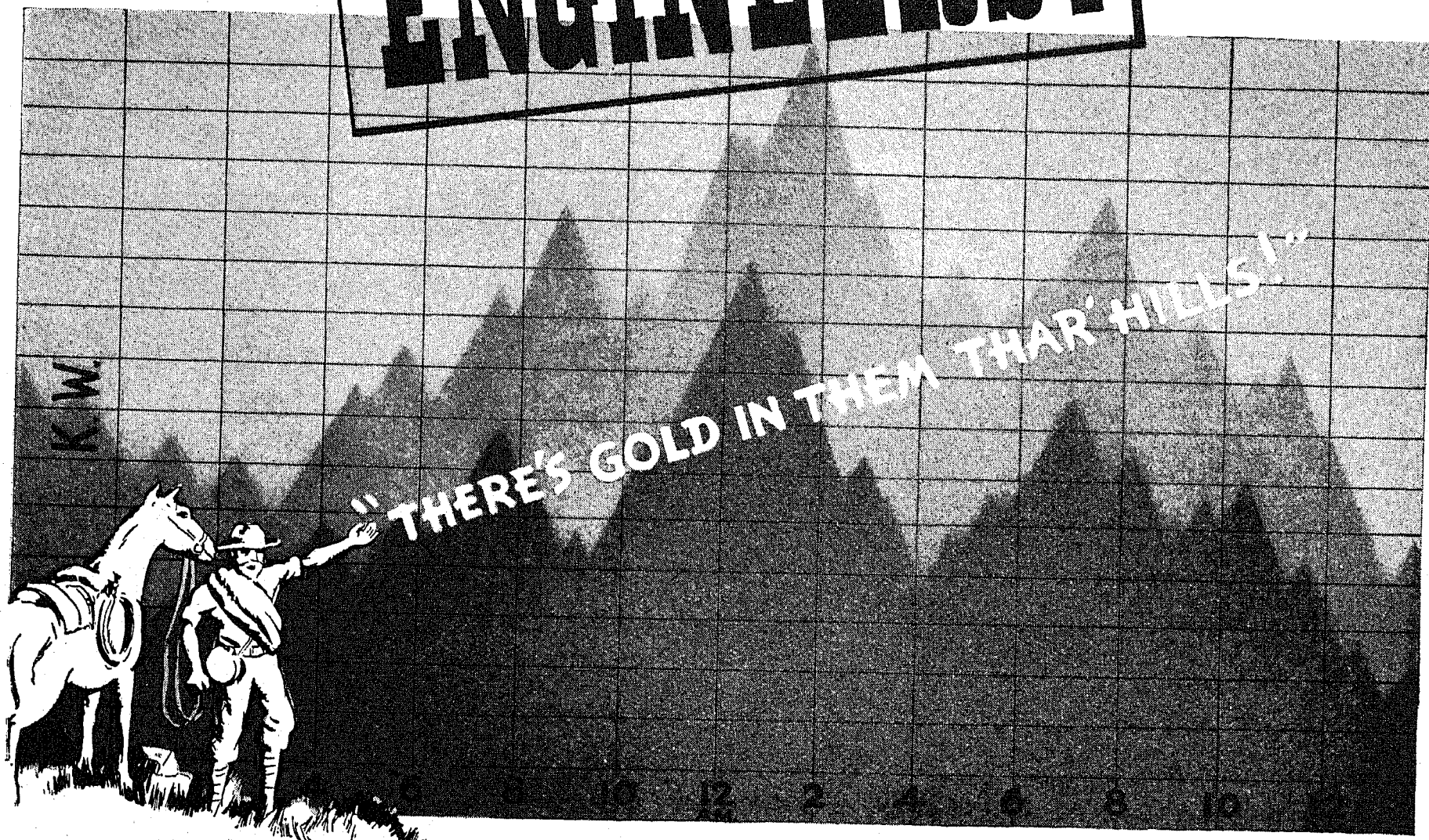
Gardiner, Alexander Charles.	Patel, Shambhubhai Nar-anbhai.
Garrett, Richard Gerald W.	Perry, Arthur.
Ghazaros, Krikor.	Qureshi, Mumtaz Hussain, B.Sc.(Eng.).
Hall, Charles, B.Sc.	Raimondo, Anthony.
Hammett, John Edwin S.	Rao, Panunarty Venkata C.
Hammond, William Herbert.	Rewcastle, John Jermy.
Hitch, Frederick Alexander N., Lieut., B.Sc. (Eng.), R.E.	Samsi, Ramesh Vithal.
Hoon, Hari Krishen.	Saxena, Sharda Charan.
Kanjilal, Sanat Kumar.	Shah, Navitlal Popatlal.
Keeling, Julian Philip J., B.Sc.(Eng.).	Shanmuganathan, V. S.
Kochak, Shardar Shanker.	Shukla, Shamkar Bapuji.
Mahindroo, Mulk Raj.	Shute, Peter Francis.
Marshall, Harry William S.	Squire, Robert Frederick.
Martin, Robert Allen, B.Sc.(Eng.).	Steele, Harry Theodore.
Mascarenhas, Joseph Lawrence P.	Still, Stanley George, B.Sc. (Eng.).
Meher-Homji, Jal Arde-shir.	Tonse, Surendranath Pai.
Monteath, George Dewar, B.Sc.	Umrigar, Dharijisha Manekji.
Otto, Gert Petrus.	Vajifdar, Maneck Bapuji.
Padia, Himmatlal Mankanji.	Venkatvaradan, Bindig-navle Ramanna.
Paramu, S.	Vigors, Philip Doyne.
Parodhad, Ram.	Watt, Arthur Muir.
	Widdowson, John Owen.
	Wild, Henry John, B.Sc. (Eng.).
	Winglee, Cecil Ng.

The following transfers were also effected by the Council at their meeting held on the 25th April, 1940:—

Student to Graduate

Baguley, Peter William.	Jones, Richard James.
Barraclough, John Francis.	Lea, Charles Arthur.
Bendre, Shardachandra Shioram.	Lishman, John Fairless.
Borup, Arno.	McIndoe, William Arthur.
Bruce, Alan, B.Sc.(Eng.).	McMorran, Fergus William, B.Sc.(Eng.).
Burrows, Arthur Thomas, Sec. Lieut., R. Signals.	Maunder, Augustine Hamilton, B.Sc.
Chandrasinghe, Don Paul.	Morley, Stanley John, B.Sc.
Constance, Ernest Raymond.	Nixon, John Roger.
Dey, Sukumar, B.Sc.	Owen, George Rhonwy, B.Sc.
Downey, Raymond Sinclair.	Ramsingh, Daramsingh.
Emms, Arthur George.	Rao, Mocherla Kutumba, B.Sc.(Eng.).
Francis, Edward Charles.	Reynolds, Sydney McGregor.
French, William Frederick, B.Sc.(Eng.).	Sen, Sachindranath.
Geoghegan, Joseph Francis.	Shaw, Donald.
Graham, Joseph William.	Walden, John Ernest, B.Sc.Tech.
Holcroft, Norman.	Williams, Thomas.
Ivanoff, Vladimir.	Wood, Humphrey, B.Sc.
Janes, John Douglas W.	

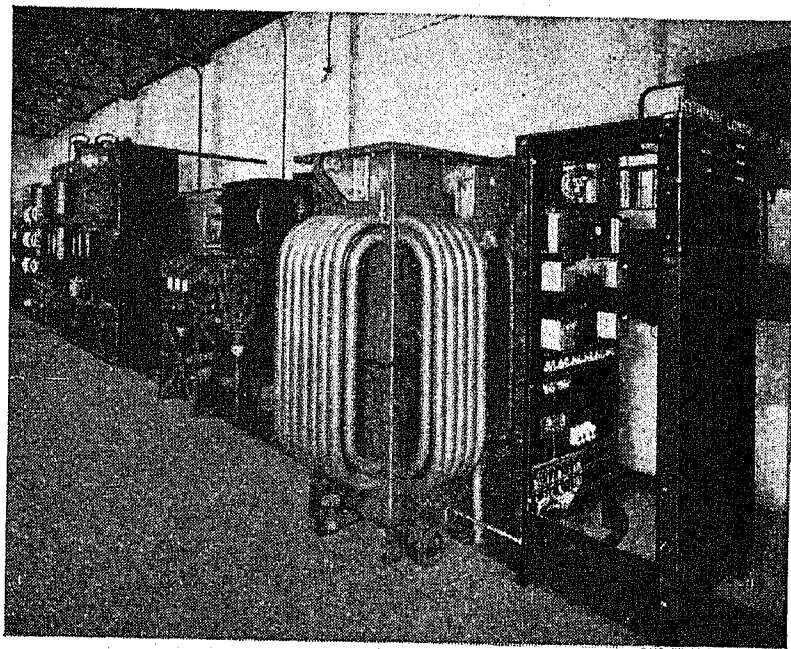
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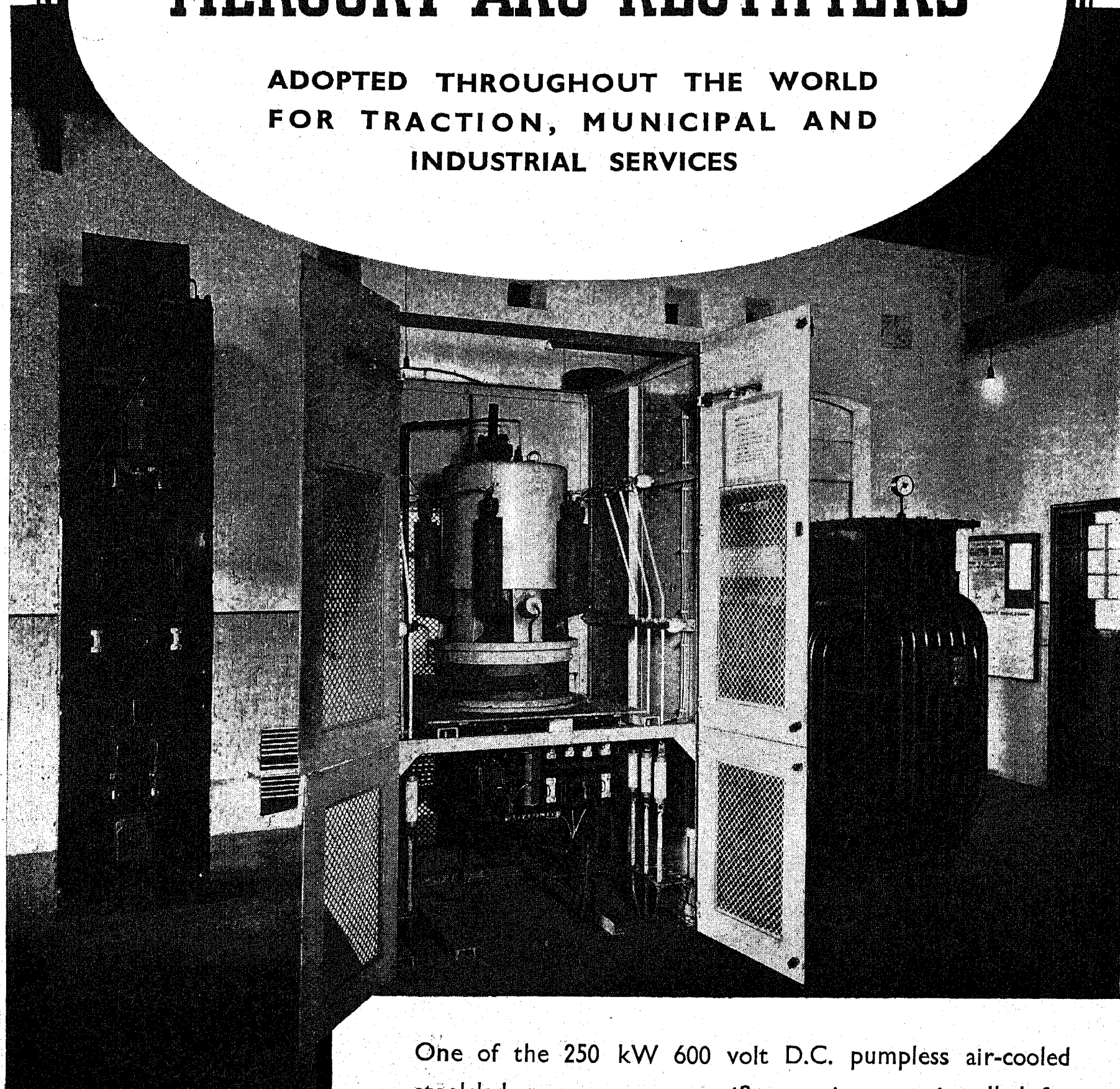
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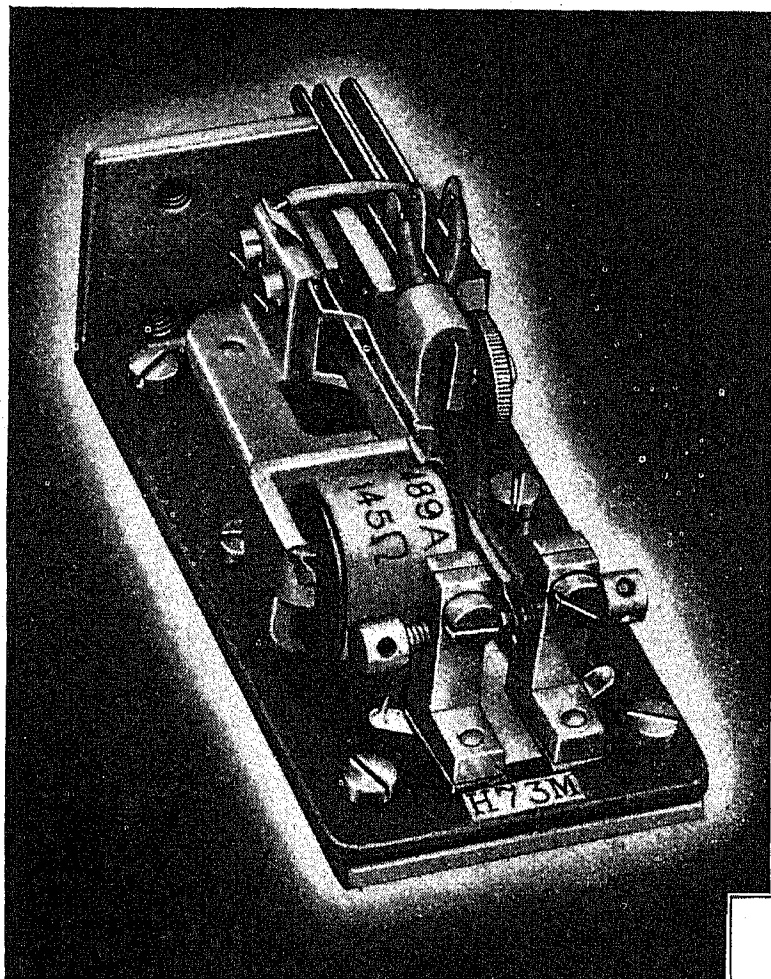
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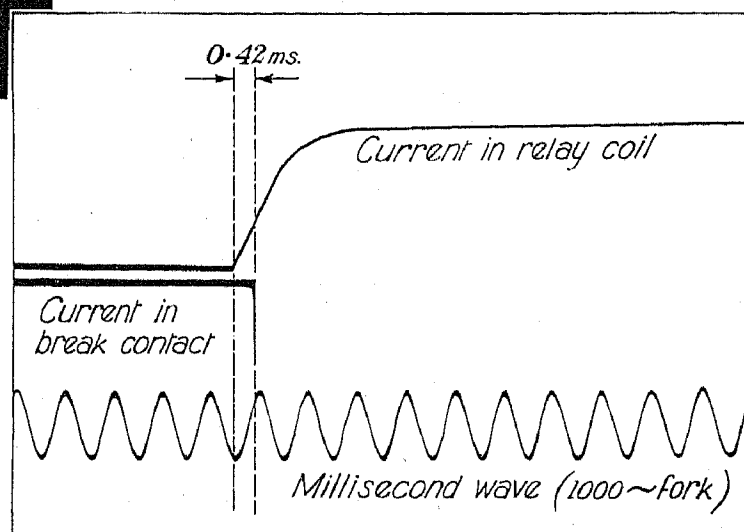
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- ★ Enabled dialling and other signals to be repeated with a degree of fidelity and reliability unattainable with other types of relay.
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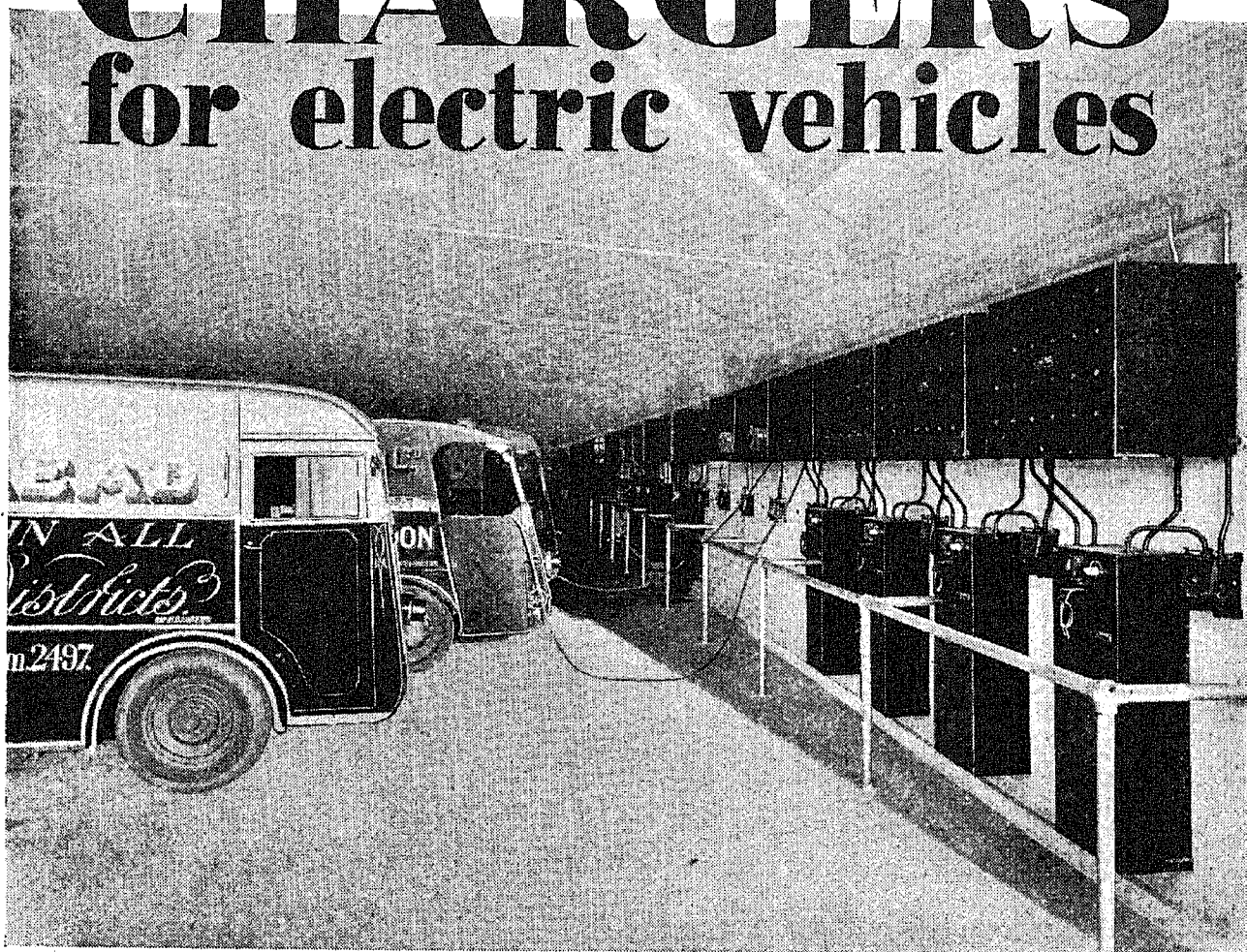
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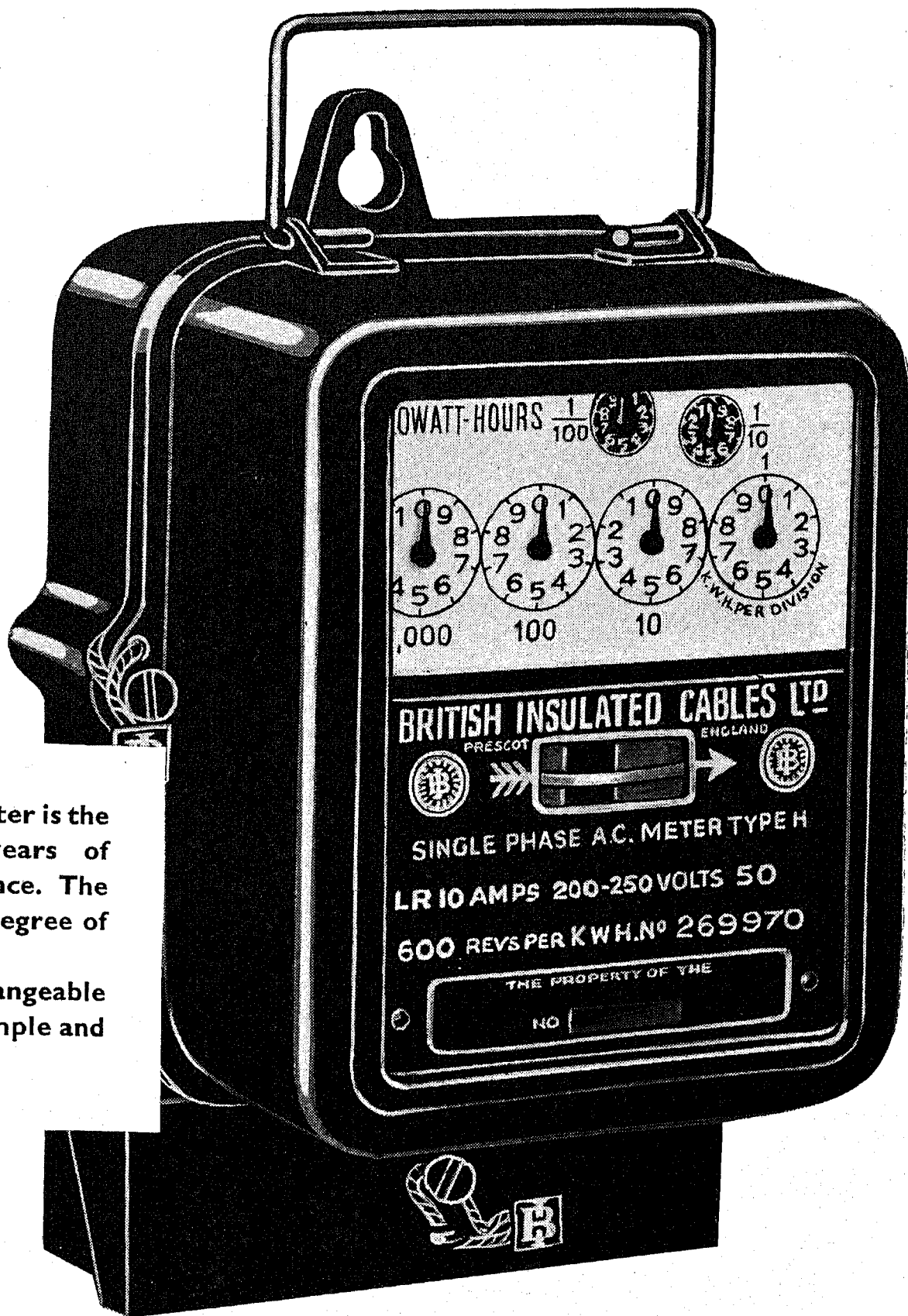
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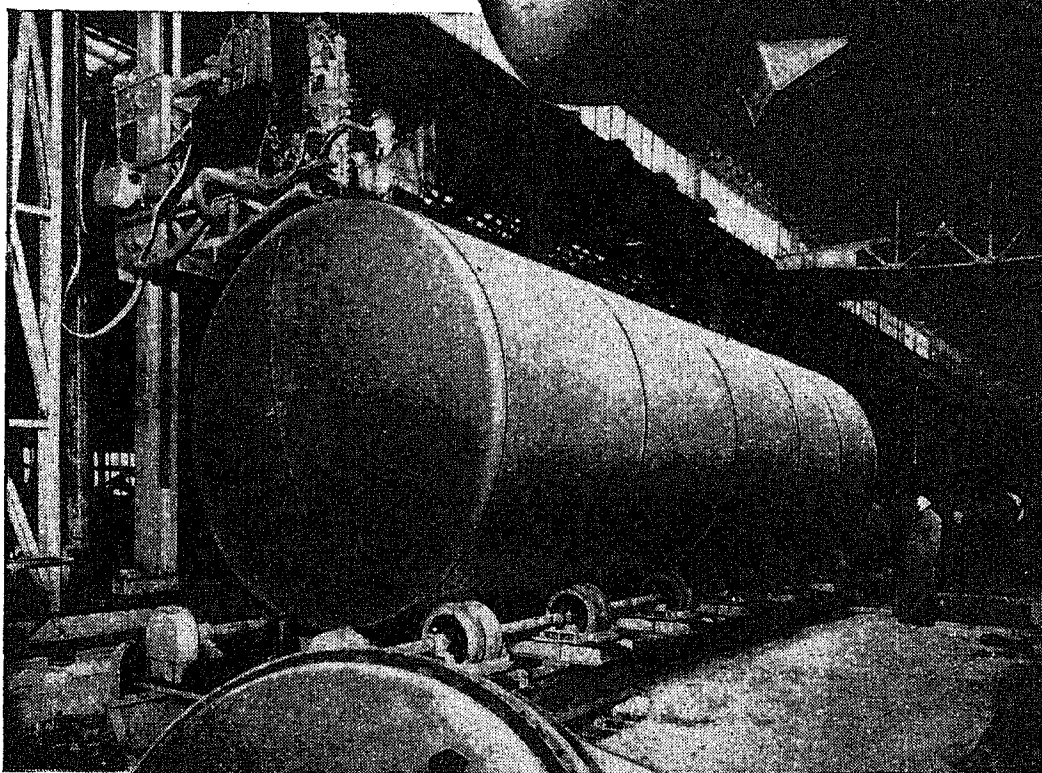
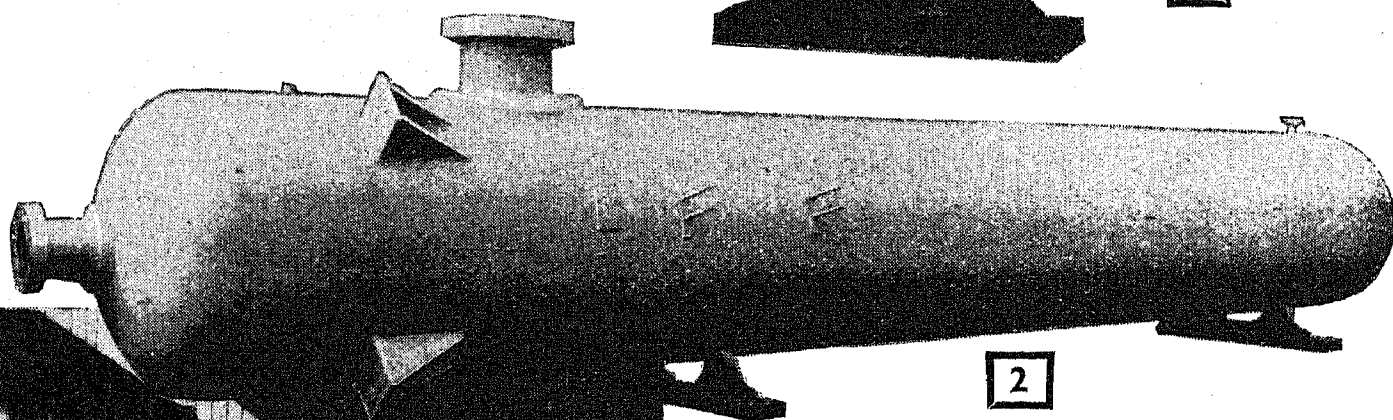
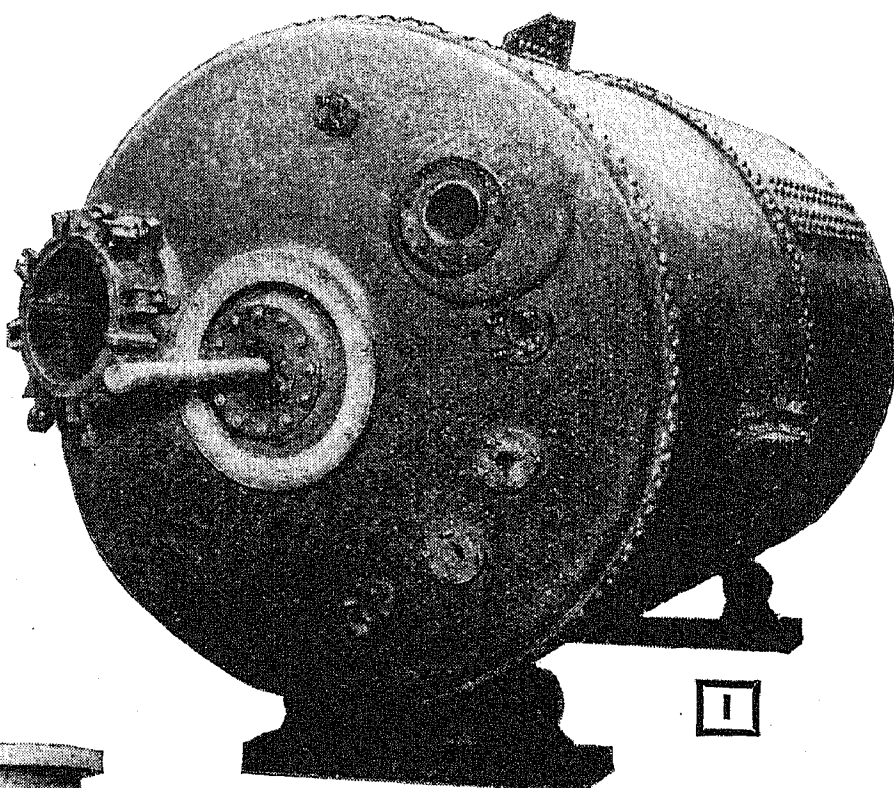
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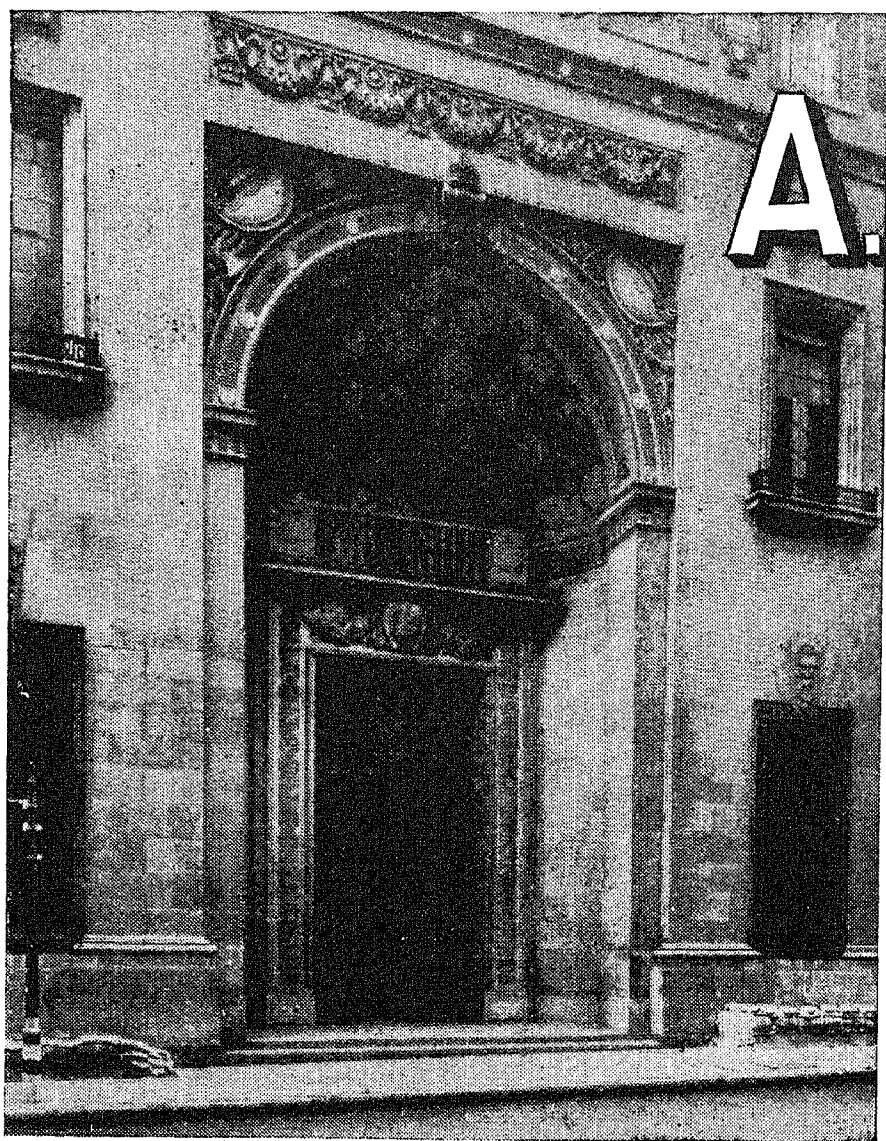
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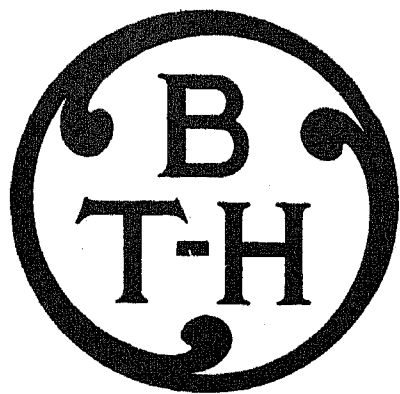
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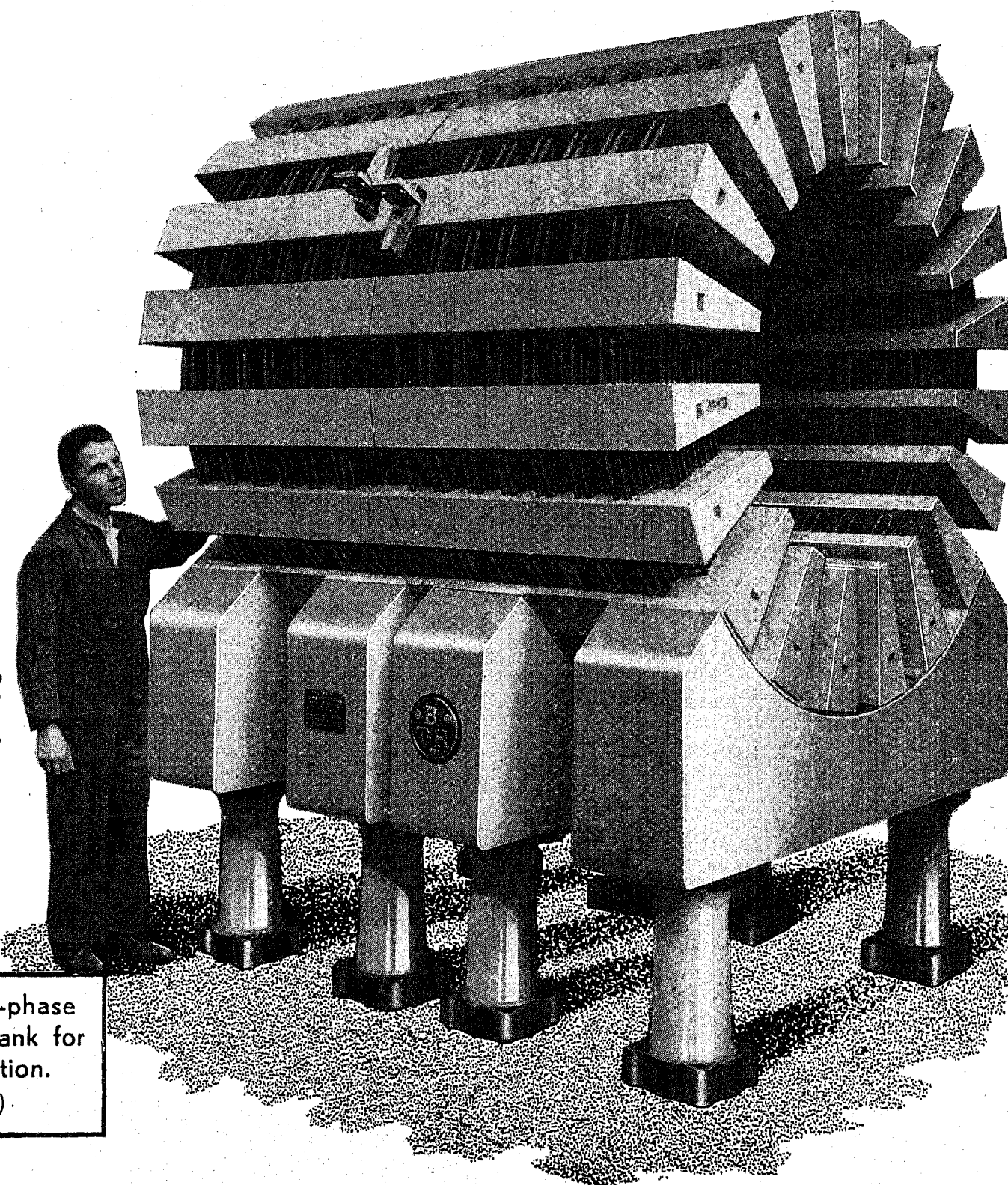
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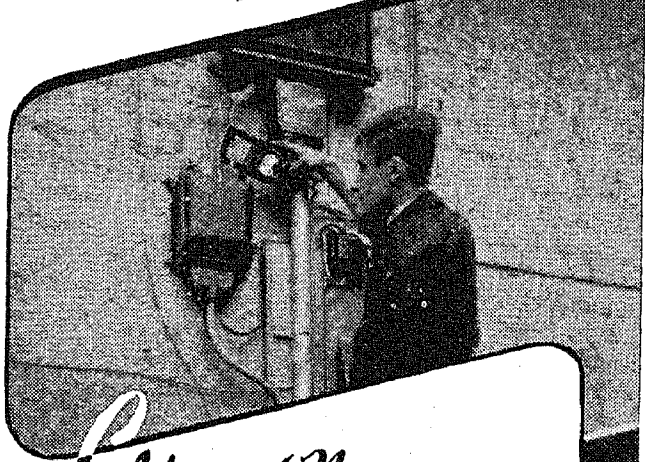
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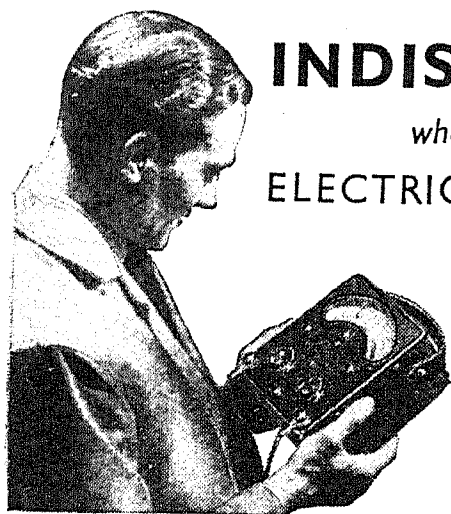
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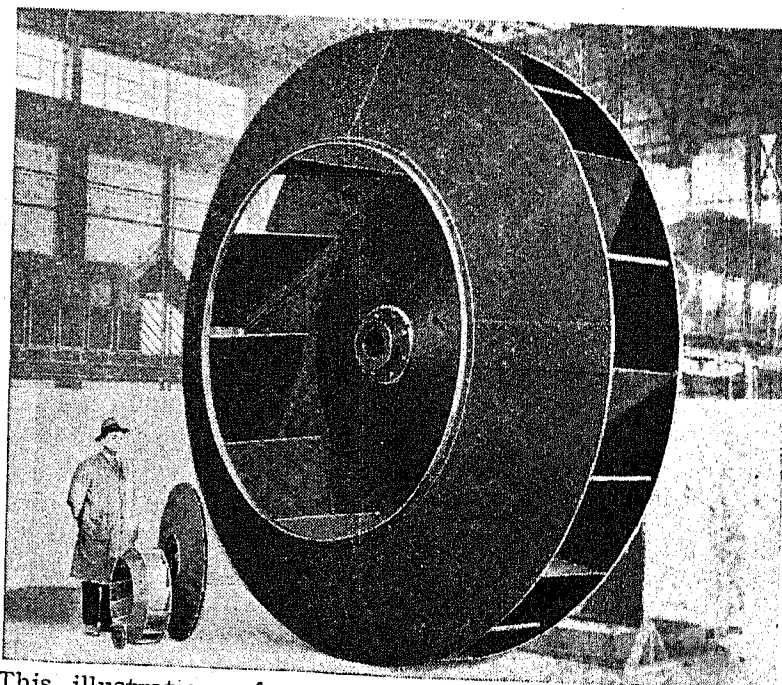
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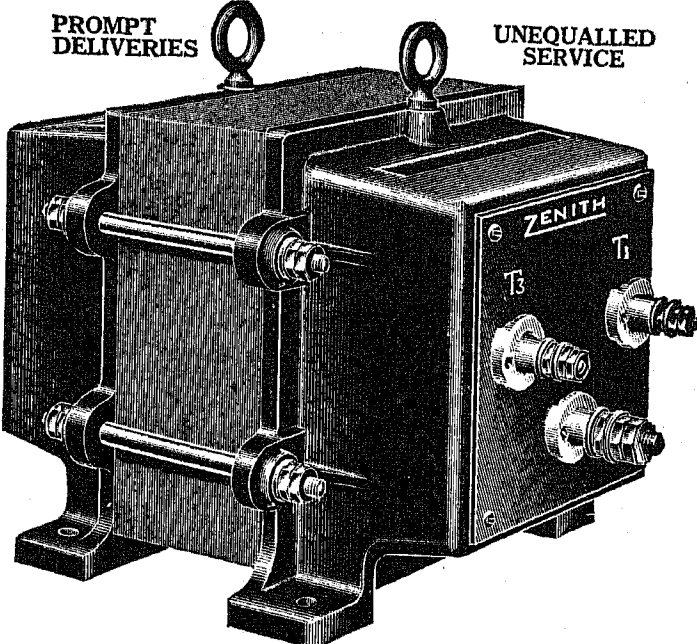
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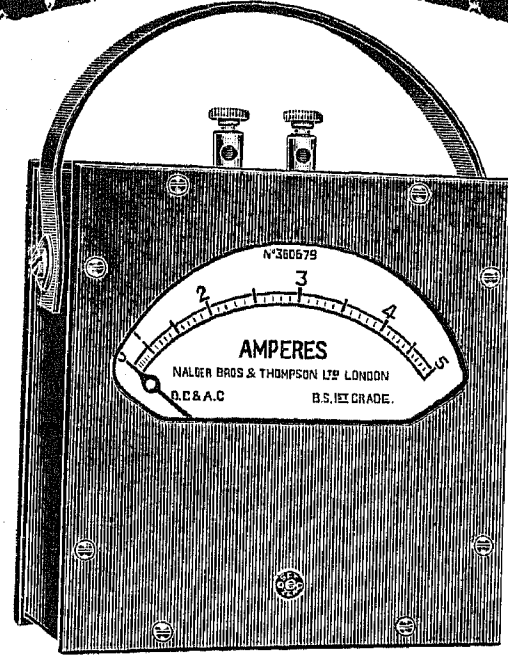
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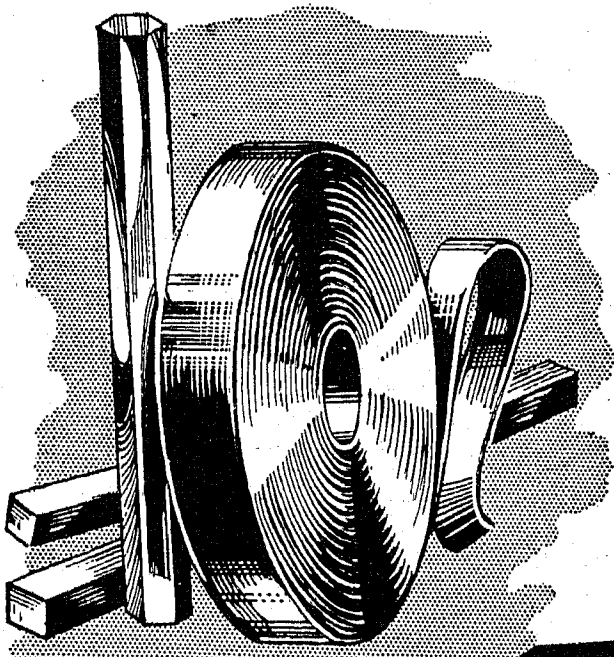
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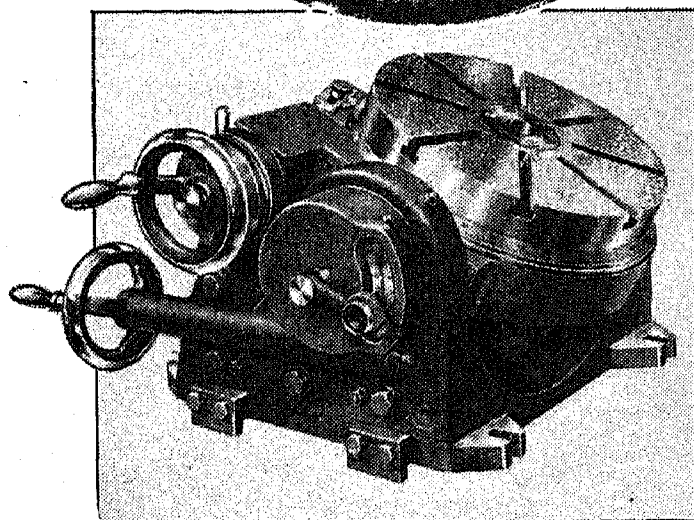
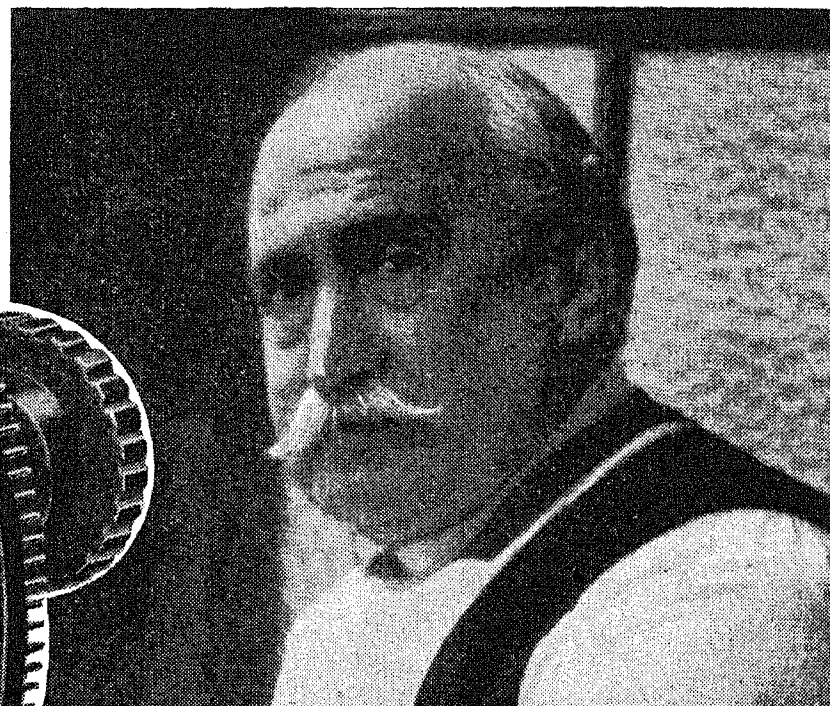
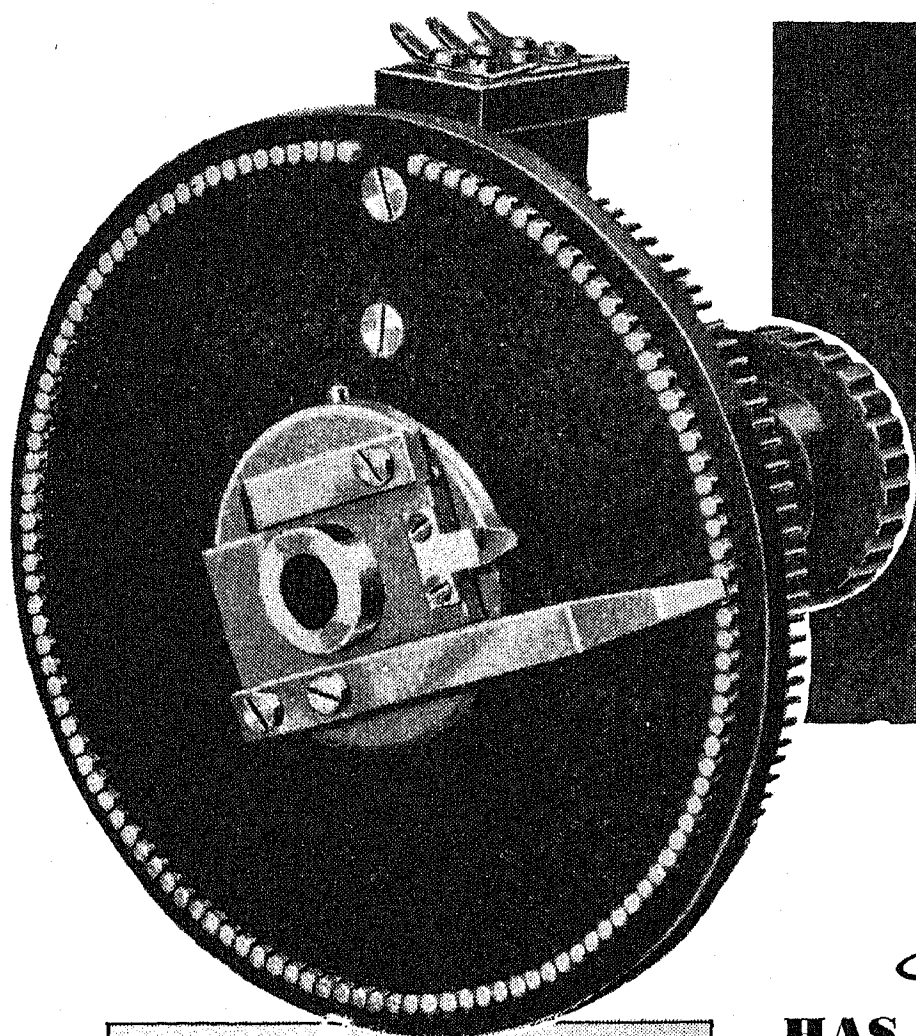
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